AN INVESTIGATION OF INCOMING SHORT AND LONG WAVE RADIATION OVER CHRISTCHURCH

A thesis
submitted in partial fulfilment
of the requirements for the Degree
of
Master of Arts in Geography
in the
University of Canterbury

by

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University of Canterbury
1976

FRONTISPIECE

Views West and East From University of Canterbury.

Taken at 10.00 a.m. on Winter Morning.

(Photo: R. Gillies)

ABSTRACT

Variations in short and long wave radiation were measured across the city of Christchurch over a five month period to mid-winter 1976. Two fixed climate stations were the basis of data collection, with mobile traverses completing the spatial pattern of urban/rural variations in radiation.

Analysis of this data showed an average attenuation of incoming short wave radiation for clear days of 14.9% in the central city, with peaks as high as 30%. A definite daily and seasonal trend was perceived with greater attenuation at lower solar elevations. These figures appear to be quite high compared with the attenuation reported from other mid-latitude cities. The atmospheric transmissivity for direct beam radiation was found to be dominantly influenced by smoke pollution, but continued attenuation in the summer months suggested the presence of pollutants not measured in this study.

Long wave radiation was also shown to have a definite urban/rural trend, with the urban excess being an average daily 8.5% for clear days which is comparable with the only other such study. The increase in long wave radiation nearly exactly balanced the short wave deficit in urban areas during daytime, but at night the urban area showed a gain in radiant energy from this source over the rural areas. Examination of possible reasons for the urban excess long wave radiation again indicated the importance of smoke pollution in radiation transfer, but the true influence of urban temperatures was thought to have been masked by an urban thermal lag found to coincide with peak incoming long wave radiation during the day.

Application of simple models to predict incoming short and long wave radiation achieved varied success, but also showed the importance of particulates in the transfer of short and long wave radiation. The use of models helped in the development of a hypothesis using the urban pollutant layer to explain the urban/rural divergence in both long and short wave radiation.

ACKNOWLEDGEMENTS

I am indebted to the many people who assisted me in this investigation. In particular I would like to thank:

Dr I. F. Owens, my Supervisor, who gave much assistant and valuable advice. The development of special computer programmes was largely his work.

Dr S. E. Tuller, Visiting Lecturer for 1975, who first stimulated my interest in urban climatology.

Mr D. Pullen of the Health Department, who provided smoke monitoring equipment and kindly provided the roof of his house for the installation of equipment.

I am also grateful for the help received during the year from Mr J. B. Hockey and the Technicians of the Geography Department, the New Zealand Meteorological Service and the Christchurch Airport Authority. Financial aid from the Geographical Society Research Fund and the Lester Fund was also appreciated.

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LIST OF SYMBOLS

ROMAN CAPITAL LETTERS

LW	Long wave radiation
LW↓	Long wave radiation towards the surface
LW↑	Long wave radiation from the surface
Q	Direct beam short wave radiation
Rn	Net all wave radiation
S.E.E.	Standard error of estimate in regression equation
SW	Short wave radiation
SW↓	Short wave radiation towards the surface
SW↑	Short wave radiation from the surface
T	Temperature
Tr	Atmospheric transmissivity to direct beam radiation
T.S.N.	True solar noon
T.S.T.	True solar time
$\overline{X}$	Arithmetic mean

ROMAN LOWER CASE LETTERS

e	Saturation vapour pressure
m	Optical air mass
q	Diffuse beam short wave radiation
r	Simple linear correlation coefficient
t	Value as test statistic

GREEK LOWER CASE LETTERS

α	Alpha, albedo
ϵ	Epsilon, surface emissivity
σ	Sigma, Stefan-Boltzmann constant

SPECIAL NOTATIONS USED IN THIS THESIS

$LW\downarrow_R$	Rural long wave radiation
$LW\downarrow_U$	Urban long wave radiation
LW urban/rural %	Urban percent long wave radiation excess
Tr_R	Rural transmissivity
Tr_U	Urban transmissivity
Tr urban/rural %	Rural percent transmissivity excess

UNITS OF MEASUREMENT

$\mu g/m^3$	Micrograms per cubic metre (volumetric measure of pollution)
w/m^2	Watts per metre squared (standard radiation energy unit)

CHAPTER ONE

INTRODUCTION

RATIONALE

Climatologists are becoming increasingly aware of the need for study in the area of urban climatology. This is in response to a number of factors. The current drive towards an understanding of Man's impact on the environment is partially responsible for this, as it is the building of city systems which is his greatest imposition on the environment. Also, the city is precisely that area where an increasingly higher proportion of the world's population is becoming concentrated.

In the past, investigations of climatic characteristics of urban areas have had two important elements:

i) the comparison of the urban area with its surrounding rural area;

ii) the investigation of urban/rural variations of climate with respect to the response elements of temperature, humidity, precipitation and fog occurrence.

This approach contributes to an understanding of the physical basis behind such differences only indirectly. Terjung (1970) states: "This approach, especially the current preoccupation with air temperature (heat island studies), appears to have little hope of leading to causal physical models and to an understanding of the complex web of inter-relations of the city-man system."

It is becoming increasingly obvious that a more effective approach in terms of understanding would concentrate attention on differences in physical attributes between cities and rural areas (for example in moisture and heat storage, albedo, turbidity characteristics and so on). These differences would be examined for their influence on the functioning of the basic processes affecting climatological parameters involved in energy and moisture budgets. The present study concentrates almost entirely on the energy balance of the city system, particularly as it is affected by atmospheric differences between the city and its countryside.

Flows of heat energy to the surface of the earth, and away from the surface of the earth obey many laws of classical physics, the most important being the law of conservation of energy. It is this law that enables the radiation budget at the earth's surface to be expressed as:

$$Rn = (Q + q)(1 - \alpha) + LW\downarrow - LW\uparrow \qquad \dots. (1.1)$$

where Rn = net all wave radiation

$Q + q$ = total short wave radiation (0.3 - 4 micron wave lengths)

Q = direct beam short wave radiation

q = diffuse beam short wave radiation

α = surface albedo (reflectivity)

$LW\downarrow$ = long wave radiation received by the surface from the atmosphere

$LW\uparrow$ = long wave radiation emitted by the surface.

This radiation budget holds equally for any part of the earth's surface, rural or urban.

The components of the radiation balance can be affected by urbanization in five major areas (Lowry, 1970):

i) surface materials,

ii) shapes of surfaces,

iii) heat sources,

iv) moisture characteristics,

v) air quality.

These have definite individual effects on radiation components and can also interact one with another to have more complex effects. The differing nature of these characteristics between urban and rural areas indicate certain areas for possible investigation of differences in radiation.

The term $(1 - \alpha)$, the proportion of incoming short wave radiation that is reflected, is dependent upon the physical characteristics of the surface medium. The modification of natural surfaces through urbanization can therefore be expected to result in changes of albedo, largely through the different colour of surfaces and the presence of vertical surfaces (Oke, 1974). Cities usually have darker surfaces which result in lower albedo and increased surface temperatures.

Outgoing long wave radiation ($LW\uparrow$) is equally dependent upon surface characteristics. The standard equation for long wave radiation emittance from a surface is $LW\uparrow = \epsilon \sigma \; T_s^4$ .... (1.2)

where: ϵ = surface emissivity

σ = Stefan-Boltzmann constant

T_s = surface temperature.

Clearly both ϵ and T_s are surface properties and as such are considerably altered in the city from the natural environment, the greatest difference being that the city surface materials have a relatively high thermal admittance and storage capacity (Oke, Yap and Fuggle, 1972). The law holds similarly for $LW\downarrow$ where the atmosphere can have variations in ϵ and T.

The main components dealt with in this thesis are the incoming ones of short wave and long wave radiation. Direct and diffuse beam short wave radiation and incoming long wave radiation are not directly affected by surface properties, but they are strongly influenced by the state of the atmosphere. Most of the factors affecting the incoming radiation components are mentioned in general texts such as Sellers (1972).

<u>Incoming long wave radiation</u> is affected by:

i) particulates in the atmosphere which absorb SW and reradiate LW radiation;

ii) water vapour which also absorbs SW and reradiates LW radiation;

iii) the temperature of the atmosphere (if the temperature of water vapour, gases or particles in the atmosphere is high they will radiate a greater amount);

iv) the amount of reradiated LW off the earth's surface which is trapped and directed downwards once again;

v) various gases which absorb LW radiation such as CO_2, O_3, NO_2 and SO_2;

vi) physical obstructions which cut out atmospheric LW radiation and impose their own radiation regime.

<u>Incoming short wave radiation</u> is affected by:

i) particulates in the atmosphere which absorb or scatter SW radiation;

ii) water vapour which also causes absorption and scattering;

iii) gases which cause absorption and scattering (Rayleigh scattering);

iv) the earth/sun distance;

v) the relative amount of atmosphere that the radiation has to pass through;

vi) physical obstructions at the earth's surface which interrupt the passage of SW radiation.

It is therefore clear that urbanization can have potentially great effects on the downward transfer of both LW and SW radiation. In the construction of cities Man inadvertently alters the amount of water vapour, the concentration of certain gases, the temperature and, most importantly, the amount of dust in the atmosphere (Chandler, 1965). In a polluted atmosphere the absorption and scattering of radiation becomes very complex. It has been found that particulate matter is a most efficient absorber of incoming short wave radiation with water vapour being the most efficient naturally occurring reduction agent in the atmosphere (Sanderson <u>et al.</u>, 1973). In this thesis the major concern is with urban effects on the downward transfer of both LW and SW radiation.

PREVIOUS INVESTIGATIONS

Work done on the energy balance of the city system is limited despite the recent worldwide upsurge of interest in the topic. Work in this field in New Zealand is non-existent. The only related studies have been by Sham (1968) and Kingham (1969) on the 'heat island' effect in Christchurch, these being of the response type parameter studies as mentioned before. Their work will be mentioned later in this thesis when discussing the variables responsible for differences in radiation across the city.

Incoming Short Wave Radiation

The urban effects of SW radiation are better documented than those for LW radiation. The amount of SW radiation received at the surface could be expressed as:

$SW\downarrow$ = f (aerosols, water vapour, atmospheric gases, cloud amount, wind speed/direction, atmospheric mixing depth, view factor, atmospheric path length). However, few studies have attempted to unravel any of the complex interrelationships involved. At most they concentrate on the measurement of absolute values of urban/rural SW difference in response to perhaps one variable.

One of the first documentations of the effect of a smoky atmosphere on the transmission of solar and long wave radiation was made by Hand (1943). With the passage of smoke from a forest fire he noted that there was a decrease in the amount of short wave radiation and little effect on long wave radiation.

The concern about pollution and the fear that Man may have started irreversible trends in the evolution of atmospheric energy parameters stimulated intense research effort in urban climatology in the 1950's. The importance that the atmosphere's smoke content has on the transfer of solar radiation was re-emphasised by Mateer (1961). From a twenty year data base for Toronto he found that the average total solar radiation on Sunday was 2.8% greater than for weekdays and this was attributed to the weekly cycle of industrial pollution. The difference was emphasised in the winter (heating) months. Bach (1973) found a similar trend for Cincinnati amounting to 3.6%.

Monteith (1966) summarised data on particulate concentrations and solar energy for a central London site and an inner suburban site (Kew) over a period from 1957 to 1963 whilst smoke controls were being enforced. This data shows very well the relationship between particulate loading and solar radiation (Table 1.1). For the two sites, it compares the real income of radiant energy with the hours of sunshine as a guide to possible receipt of energy. This ratio gives an index of atmospheric transmission. Over each year, smoke in central London decreased by about 10 $\mu g/m^3$ while solar radiation increased by 1%, showing a strong and consistent relationship between smoke and radiation attenuation.

Jenkins (1971) also noted the effect of the smoke abatement program on increased hours of sunshine in central London. Using data averaged over the years 1958 to 1967 as compared with the 30 year averages to 1960, he found little change in warmer months but considerable increases in sunshine over the winter months (Table 1.2).

Recent studies have tended to concentrate more on contributing to a better understanding of the urban heat balance. They tend to confirm previous estimates of depletion and add to the statistical base. Long term studies include one by East (1968) for Montreal where he found an average urban attenuation of total solar radiation of 9%, with a distinct seasonal trend, with summer values as low as 4% and winter values as high as 15%. This cycle was in phase with a seasonal air pollution cycle. Yamashita (1970) found a general decrease of 10% in total solar radiation under clear skies for Tokyo. Further study indicated a weekly trend superimposed over a yearly trend and a variation in depletion due to wind direction (and therefore the sector contributing pollution).

TABLE 1.1

Annual Mean Values of Daily Direct Radiation (mw hr cm^{-2}) S, Hours of Sunshine n, and Smoke Concentration ($\mu g/m^3$)

	KEW				CENTRAL LONDON			
	S	n	S/n	Smoke	S	n	S/n	Smoke
1957	109	4.29	25.5	90	80	3.82	20.9	343
1958	86	3.80	22.7	94	69	3.34	26.6	234
1959	130	5.07	25.6	93	120	4.76	25.2	222
1960	102	4.13	24.7	70	84	3.93	21.4	160
1961	105	4.40	23.9	72	91	4.25	21.4	123
1962	107	4.08	26.2	73	100	3.97	25.3	103
1963	99	3.94	25.1	74	99	3.72	26.6	105

From Monteith (1966)

TABLE 1.2

Monthly Increases in Sunshine for 1958-67 Period Over 1931-60 Period.

	October	November	December	January	February	March
Sunshine Hour Percent Increase	15	30	60	41	25	15

From Jenkins (1967)

Nishizawa and Yamashita (1968) indicated a strong relationship between transmissivity and wind speed. Differences between urban and rural stations were found to decay exponentially with increased wind speed.

Probald (1972) showed long term total solar radiation data for Budapest indicating a radiation deficit for urban stations compared to rural caused by turbidity of the polluted urban air amounting to an average 7-8% with winter amounting to 15%. Short term studies indicating urban/rural short wave radiation differences include those by Bach and Patterson (1970), Rouse and McCutcheon (1972) and Sanderson et al. (1972). These results are all included in a summary table (Table 1.3). Sanderson (1974) examined atmospheric transmissivity values (the proportion of direct beam radiation transmitted by the atmosphere if the sun were directly overhead) on clear days for a site at Windsor, Ontario, and found that transmissivity averaged 0.65 and varied seasonally with air quality.

Some studies have included the variation of attenuation of SW radiation with height over urban areas. McCormick and Baulch (1962) found considerable attenuation in the layer between the surface and 200 to 500 metres at Cincinnati. It was concluded that the height of the urban atmosphere can extend up to 1 kilometre, but that the profile of transmissivity varied greatly due to differences in meteorological and pollution conditions. Bach (1971) found similar results for the same city.

To summarise, SW radiation (0.3-4.0 micrometers wavelength) is depleted in a polluted urban atmosphere by an average 10-15% as compared to a clean rural site. Attenuation is greatest for heavily polluted atmospheres and when the solar path length is large (high solar zenith angles). As well as the gross depletion of total solar radiation, the spectral and directional character of the beam changes. The shorter wave lengths especially are filtered out (Randerson, 1970), and the proportion of diffuse beam SW radiation to direct beam SW radiation is

TABLE 1.3

Previous Studies of Urban SW$\downarrow$ Depletion

Author(s)	Location	Average Depletion %	Maximum Depletion %
Annual averages (all weather)			
Emslie (1964)	Toronto	5-10	
Probald (1972)	Budapest	7- 8	up to 15%
Monteith (1966)	London	20	
	Suburb. London	8	
Detwiller (1970)	Paris	6-20	up to 20%
East (1968)	Montreal	9	up to 25%
Sekihara (1973)	Tokyo	10-15	
Studies on cloudless days			
Sanderson (1973)	Windsor(Ont.)	10	up to 25%
Yamashita (1970)	Tokyo	10	
Yamashita (1973)	Toronto	5- 15	
Bach (1969)	Cincinnati	6	
Rouse and McCutcheon (1971)	Hamilton(Ont.)	12	up to 20%

increased (Robinson, 1962). This has important implications for measurement, as most studies in the past have only measured total solar radiation. This masks the actual attenuation of direct beam radiation, because a large proportion of the lost direct beam is regained as diffuse radiation. For example, Sprigg and Reifsnyder (1972) found that direct beam SW radiation losses averaged up to 25% in polluted air; however, up to 80% of this was regained at the surface as diffuse beam to be counted as total radiation.

Apart from climatic effects of variations in SW radiation, Oke (1974) mentions some other important consequences. The filtering and scattering of radiation is important in visibility, lighting and colour perception. Similarly the reduction of the shortest wave lengths has implications for tanning, Vitamin D production and skin cancer in humans, and for organic photosynthesis.

Incoming Long Wave Radiation

Urban/rural variations in long wave radiation are poorly understood and documented and this results in a certain amount of confusion and controversy. The reasons for this are several, not the least of which is the lack of intensive studies in this area of urban climatology around the globe. One other problem is the small energy differences that are involved, which are less easily measured than SW radiation.

It has generally been found that pollutants will decrease short wave radiation and it has been felt that this would in turn increase incoming long wave radiation. The hypothesis has been that an aerosol layer over the city absorbs some incoming SW and outgoing LW during the day, and outgoing LW at night, then reradiates this heat energy with a large proportion of it arriving at the surface as LW$\downarrow$. This is the much publicised "green house" effect which has long been quoted as an important reason for the development of the urban heat island (Sham, 1968). Recently, however, some doubt has been cast on this hypothesis.

The main criticism is based upon the observation that any surplus energy obtained in this way in the city is unlikely to be sufficient to develop a heat island (Oke and Fuggle, 1971).

Bach and Patterson (1969) in a limited series of measurements in Cincinnati found an increase of LW$\downarrow$ up to 8% in the central city as compared to a rural zone. However, differences were usually within instrumental error and therefore little confidence could be placed in them. Idso (1972) noted a substantial increase in LW$\downarrow$ during an Arizona dust storm. A later analysis of temperature records at Phoenix, Arizona, indicated a warming trend which could be isolated and identified with a build-up of atmospheric pollution which enhanced the "green house" effect (Idso, 1974).

Lettau and Lettau (1969) discussed the attenuation of solar radiation under various atmospheric conditions. They concluded that high turbidity in the atmosphere has the potential for increasing absorption of sunlight, which would result in atmospheric heating. Implicit in this atmospheric heating is an increase in the LW$\downarrow$ to the surface. Similarly, Atwater (1971) showed that concentrations of nitrogen dioxide of 1 ppm could lead to strong atmospheric heating through absorption of solar radiation, and that a concentration of gases such as CO_2, SO_2 and NO_2 could lead to greater absorptivity of terrestrial LW$\uparrow$.

Recent studies by Oke and Fuggle (1971) and Rouse <u>et al.</u> (1973) indicate a slight urban excess of LW$\downarrow$ on cloudless nights. The latter also had daytime data suggesting an urban LW$\downarrow$ excess of up to 33% at midday. The reasons for the LW$\downarrow$ increase can only be explained by:

i) an increase in atmospheric emissivity over the city as a result of changes in atmospheric constituents which would affect the exchange of LW radiation;

and/or ii) an increase in urban air temperature as a result of non-radiative warming of the atmosphere through the turbulent sensible heat flux set up by artificial heat generation and stored heat in the city.

Oke and Fuggle (1971) tend to follow the second hypothesis. The urban/rural energy difference detected by them was usually less than 5%. This was equated with the lapse profile of the urban sites which gave cooler radiating temperatures above and the inversion profile at the rural sites which gave warmer radiating temperatures above. From this simple consideration, and in the absence of vertical profiles of water vapour and temperature, it appeared that rather than an increase of atmospheric emissivity from such constituents as water vapour and pollution, the greater emissivity was due to urban warmth. Hence, Oke and Fuggle decided that the observed increase in LW$\downarrow$ was probably an effect rather than a cause of the urban heat island. The low percentage difference precluded any possibility of it being a sufficiently large forcing function to give measured amounts of urban heat excess.

Rouse et al. (1973) follow the first hypothesis. They took atmospheric radiative temperatures at 150 m and 2500 m above both industrial and control sites and found them to be similar. Therefore the application of Stefan Boltzman's equation ($LW\downarrow = \epsilon\sigma T^4$) and the measured energy flux gave a computed sky emissivity which was significantly different for both sites. For the industrial site, they noted that total incoming radiation ($SW\downarrow + LW\downarrow$) remained almost identical with the control site. Therefore the decrease in SW$\downarrow$ was being exactly balanced by an increase in LW$\downarrow$, the interpretation being that when part of the SW was absorbed by pollution it was immediately reradiated as LW$\downarrow$ and LW$\uparrow$. As the total radiation reaching the surface was the same for both sites, it was further hypothesised that an increased absorption of outward LW flux from the warm city surface provided this missing energy. At night, site differences were found to be much less and this was ascribed to the lack of SW$\downarrow$ on the polluted layer over the industrial site, resulting in atmospheric cooling to give a more similar LW$\downarrow$ value for both sites, with a slight industrial excess due to the residual effect of the day.

These two studies are the most comprehensive on the urban/rural $LW\downarrow$ flux. However, they cannot be compared directly. One relates only to the nocturnal situation and the other almost entirely to the daytime situation. Neither of these studies attempts the integration or isolation of other likely controlling variables.

Sanderson (1974) supported the observations made by Rouse <u>et al.</u> (1973) that atmospheric radiation reached a maximum at solar noon, and suggested that this was due to absorption and reradiation of LW by particulates in the atmosphere at the time of greatest city surface warmth. However, the statement that $SW\downarrow$ energy lost at the surface was regained as $LW\downarrow$ in polluted urban environments was not substantiated by Sanderson. She suggested that the reduction in $SW\downarrow$ represented a real loss of energy income, because of the albedo of the polluted urban atmosphere.

A study by Probald (1972) of the heat balance of Budapest supported Oke and Fuggle's statement that any urban/rural differences in $LW\downarrow$ are small, amounting to 1% on an annual basis. (Note that the other studies were all short periods of less than 20 days.) Probald also concluded that it was unjustified to attach great importance to the "green house" effect in the formation of the heat island.

In conclusion; whilst all studies agree that there is an excess of $LW\downarrow$ over polluted urban areas, most state the difference to be $<5\%$. There have been no further studies to substantiate the larger differences reported by Rouse <u>et al.</u> It is in the area of LW radiation flux rather than in any other area of urban radiation climatology that there is a need for further research.

<u>AIMS AND APPROACHES</u>

A consideration of previous investigations within the available instrumental constraints suggested that intensive study of variation in urban and rural downward radiation would be of use, especially if supplemented by transect data. In addition, the value of considering a large range of potentially influential atmospheric factors was recognised.

Hence the aims of this study can be concisely stated as:

i) a description of urban/rural differences in LW$\downarrow$ and SW;

ii) a description of the spatial variations in LW$\downarrow$ and SW;

iii) an explanation of these variations in terms of the major atmospheric variables of particulate loading, water vapour, temperature, cloud, vertical stability, wind speed and direction.

Whilst it is realised that a more complete solution awaits measurements of other aspects of the radiation balance, such as LW$\uparrow$, surface albedo, evaporative and sensible heat flows, a broader aim is to contribute to the understanding of the city's effect on the radiation microclimate.

This study may have some advantages over earlier studies of the incoming radiation regime of cities. Firstly, it examines both long and short wave radiation together which is desirable as they are interrelated to a large degree. Secondly the study is at two levels; it examines long term radiation variation for a fixed urban and rural site, as well as short term spatial radiation for selected days at numerous sites across the city. Other studies have usually only employed one or other of these methods and have therefore missed out on the true pattern through time and space. The examination of several possible reasons for variation in radiation rather than just one or two is another advantage. This study, by looking at both incoming radiation components and variables outlined in iii) above, may go some way towards explaining some of the problems, at least for the Christchurch city area. There are also some advantages with using Christchurch as a laboratory for such a study. The relief is uncomplicated, yet provides a hill and marine effect if needed. The urban/rural cut off point is well defined and symmetrical, and the winter climate is suitable for studies involving air pollution. The city is large enough in area and population to exhibit all the known urban climatic effects.

The need to expand the data base is particularly important, as our understanding of the most basic energy exchanges, necessary for sound climatology, is almost totally lacking for the urban environment. At present there is a drive to produce workable atmospheric dispersion models which take account of the complexities of the urban interface. Oke and Fuggle (1971) consider that the ability to model has outstripped the physical data base. The use of unfounded assumptions for input data gives little chance of validating outputs against the real world situation. This therefore is of major consideration in this thesis.

CONCEPTUAL FRAMEWORK AND THESIS FORMAT

In order to achieve the aims as outlined above, three procedures are used. These are:

i) the measurement of SW$\downarrow$ and LW$\downarrow$ across the city from both fixed stations and transects;

ii) the analysis of the measured values;

iii) the comparison of the measured radiation values with other measured variables to show the relation of downward energy fluxes to other variables in the climate of the city.

The integration of these procedures in the structure of the study is diagrammatically shown in Figure 1. 1. The asking of certain questions as to the radiation climatology of Christchurch leads to a consideration of theory on the subject. This, in association with certain background information (climatic and non-climatic) about Christchurch leads to the formation of an empirical structure in order to answer the original question. The collection of data is followed by analysis and conclusions as to the absolute variation of SW$\downarrow$ and LW$\downarrow$ over Christchurch and an explanation of the influences of other variables.

FIGURE 1.1

CONCEPTUAL FRAMEWORK FOR THESIS

QUESTIONS

1) How does S. W.$\downarrow$ and L. W. $\downarrow$ vary across Christchurch?

2) What independent parameters are associated with this variation)

FIELD (Chapter 2)

1) Fixed Site
   Urban/rural observations:
   a) S. W.$\downarrow$ and L. W.$\downarrow$ over time.
   b) Associated parameters.

2) Traverses:
   a) S. W.$\downarrow$ and L. W.$\downarrow$ through space.
   b) Associated parameters.

THEORY (Chapter 1)

1) Predicted S. W. $\downarrow$ across urban/rural areas with respect to dust, water vapour, wind speed, wind direction, zenith angle of sun, and atmospheric stability.

2) Predicted L. W.$\downarrow$ across urban/rural areas with respect to temperature, water vapour, dust, wind speed and direction and atmospheric stability.

ANALYSIS (Chapters 4, 5 and 6.)

1) Testing for urban/rural differences in S. W.$\downarrow$ and L. W.$\downarrow$

2) Comparing differences through time.

3) Comparisons between theory and field data.

4) Investigations of associated parameters' influence on S. W.$\downarrow$

5) Investigations of associated parameters' influence on L. W.$\downarrow$

6) Spatial variation of S. W.$\downarrow$ and L. W.$\downarrow$ in response to associated parameters.

CONCLUSIONS (Chapter 7)

1) Urban/rural difference in S. W.$\downarrow$ and L. W.$\downarrow$
   Summary of general characteristics for Christchurch.

2) General explanations and discussions of areas for further research.

The above conceptual framework dictates the thesis format. After this introductory chapter, Chapter 2 outlines the materials and methods used. Chapter 3 discusses the climate and air quality of the study area, and includes a general analysis of some atmospheric variables as measured over the study period inside and outside of the city. Chapter 4 examines urban/rural differences in SW$\downarrow$ at the two fixed sites over the summer-winter period. These differences are related to the other measured meteorological and air quality parameters in the form:
(Q + q) U/R = f (poll, wind speed/direction, vapour pressure, mixing depth ...... etc.). Chapter 5 examines urban/rural differences in LW$\downarrow$ in much the same way. Chapter 6 outlines the spatial patterns of incoming SW$\downarrow$ and LW$\downarrow$ variation as measured by the mobile traverses. Chapter 7 is a summary of the main observations and conclusions of earlier chapters that are pertinent to the principal aims of the study. This chapter also contains suggestions of areas for further possible research.

CHAPTER TWO

MATERIALS AND METHODS

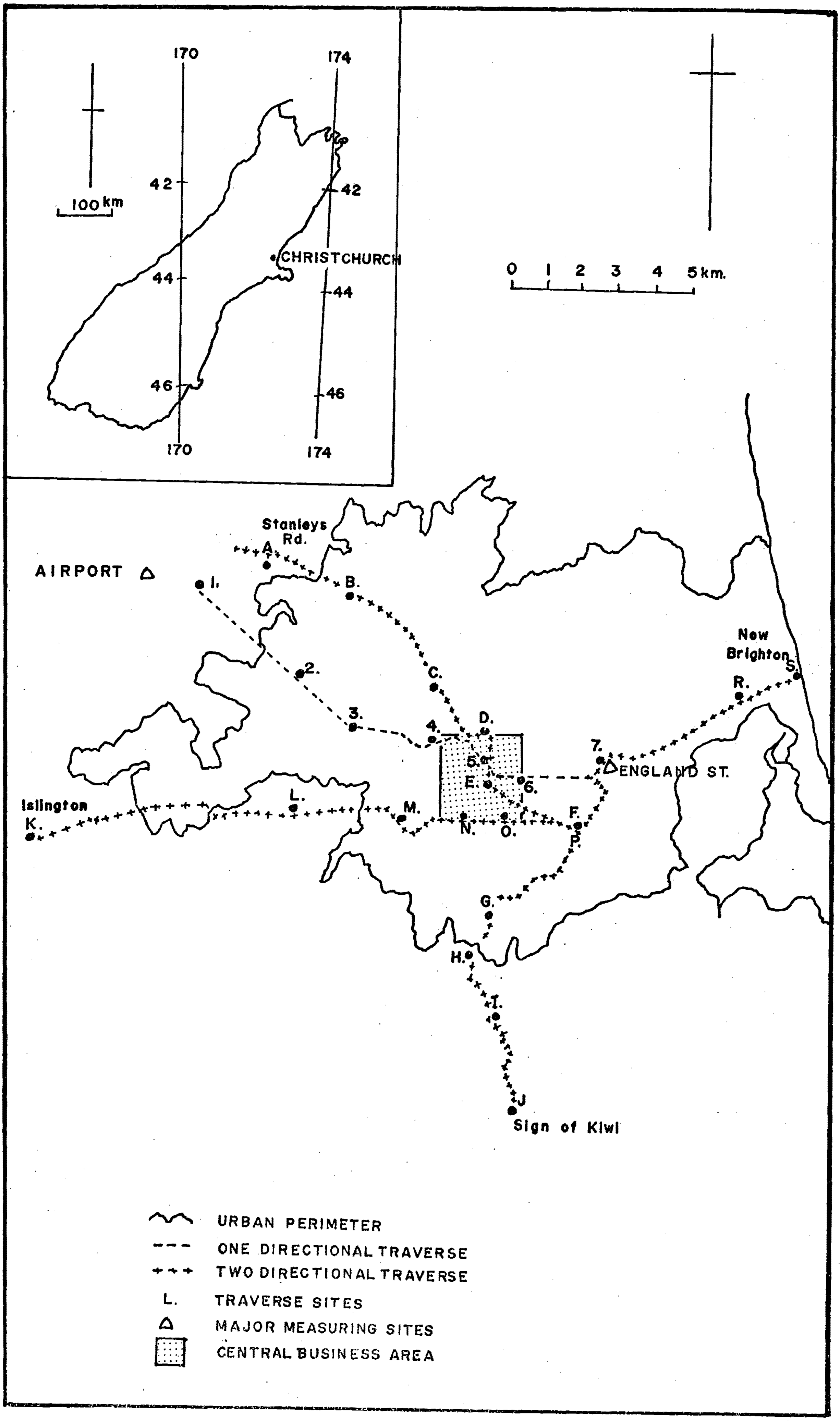
LONG TERM FIXED CLIMATE STATIONS

Because an important aim of this study was to investigate the existence of urban/rural differences in radiation, monitoring stations were established at urban and rural locations. The urban climate station was located on the roof of a private house in England Street, Linwood, about 1 km east of Bealey Avenue (Figure 2.1). This site is situated in an inner suburb of Christchurch which consists mainly of older type housing. Reasons for choosing this site were several. Firstly, winter smoke pollution figures here are consistently higher than any other area in the city, this being probably due to the large number of open domestic fires in the area. Secondly, the house belongs to Mr D. Pullen, Chief Air Pollution Inspector in Christchurch and the Health Department have used this site for pollution measurements for a number of years. There are obvious advantages in having the urban radiation measuring sensors at the same site. The steep nature of the roof also provides an advantage in that radiation instruments are above any shadowing effects of trees and that the instruments are at a similar height above the ground to those at the rural site. The variables measured at this and the rural fixed site are included in the list in Table 2.1. More specific information is included in a later section of this chapter.

Instrumentation at the urban site included a solarimeter and a solarimeter with a shadow ring attachment to measure total and diffuse beam SW$\downarrow$, and an adapted net radiometer to measure LW$\downarrow$. These instruments were mounted on adjustable frames along the ridging of the roof (Plate 2.1).

A thermohygrograph for the continuous measurement of temperature and atmospheric vapour pressure was mounted inside a Stevenson's screen on the flat roof of an adjacent porch, 3 metres from the ground. The smoke sampler inlet was located at a similar height from the ground. Automatic recorders for all instruments were located inside the back porch of the house.

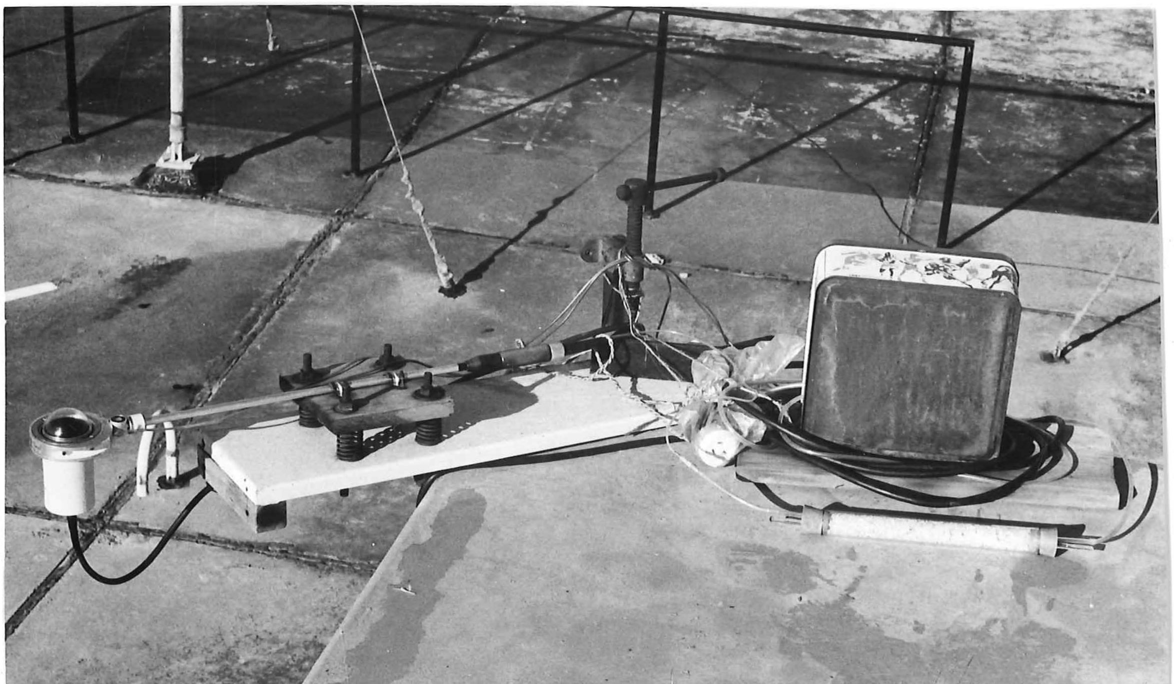
Figure 2. 1 Map of Christchurch and Location of Measurement Sites.



170
174
42
44
46
100 km
CHRISTCHURCH
0 1 2 3 4 5 km.
Stanleys Rd.
AIRPORT
Islington
New Brighton
ENGLAND ST.
Sign of Kiwi
A. B. C. D. E. F. G. H. I. J
K. L. M. N. O. P. R. S.
1. 2. 3. 4. 5. 6. 7.
URBAN PERIMETER
ONE DIRECTIONAL TRAVERSE
TWO DIRECTIONAL TRAVERSE
TRAVERSE SITES
MAJOR MEASURING SITES
CENTRAL BUSINESS AREA

Plate 2.1 Radiation Instruments at Urban Site. Shadow ring in background, solarimeter at centre and radiometer in foreground.

Plate 2.2 $LW\downarrow$ Instrumentation at Rural Site. Electric pump to the right.



The site chosen on the outskirts of Christchurch as the rural site was at Christchurch International Airport 10 km northwest of the city centre (Figure 2.1). The airport is at the end of a long avenue, and is separated from the outer suburbs of the city by a golf course and some rural land. Whilst having disadvantages as compared to a true rural site, such as the unnatural nature of adjacent surfaces and the proximity to the city proper, it also had some considerable advantages. The New Zealand Meteorological Service operates a large station at the airport including 24 hr observations of cloud, wind speed and direction, temperature and humidity, as well as taking daily radiosonde readings and recording SW$\downarrow$. Shelter and power for recording equipment was also a consideration.

There are reasons for believing that the airport is well insulated from the city in terms of air quality. As discussed in the following chapter, pollution measurements are very low at the airport and this is likely due to the fact that under conditions conducive to maximum pollution (calm, clear nights), there is usually a katabatic drainage of cold air down the plains from west to east; therefore the airport remains relatively free of pollution. Even given that the city has a slight effect on the airport's climate, observations made will give a good indication of urban/rural trends in radiation and climatic parameters. Representativeness of the respective sites is examined in more detail in a later section of this chapter.

Radiation instrumentation at the airport site was on the flat roof of the third floor administration wing at a height of 10-12 metres. A solarimeter with shadow ring attachment was located adjacent to the SW$\downarrow$ receiver of the Meterological Service. The net radiometer was located nearby at a slightly higher elevation, while recording equipment was set up in a boiler room on the roof. The intake for the smoke sampler was from the window of the third floor office with the recorder located inside. All temperature and humidity measurements were taken inside a standard Stevenson's screen 100 metres away from the main building at a height above the ground of 1.5 metres.

From this point on in this study, all reference to the England Street and airport sites will be termed urban and rural respectively.

MOBILE TRAVERSES

The technique of using mobile traverses to record trends in radiation has been used before (Oke and Fuggle, 1972), and was used in 1975 by an Honours class in climatology in this department. Although the possibility that errors will occur is increased, such techniques do give an indication of microvariations in SW$\downarrow$ and LW$\downarrow$ across a city over relatively short periods of time. Equipment used in traverses was similar to that used at the fixed sites except it was made portable by the use of battery powered millivoltmeters.

Mobile radiation traverses involved the use of a motorcar travelling a pre-determined route across the city with measurement points 1-2 km apart. The traverse one way was followed by a return traverse stopping at the same sites and the data was averaged for the two traverses. Daytime runs were oriented around solar noon so that radiation characteristics would be measured at an equivalent time away from solar noon on both runs. This enabled the systematic daily trends in SW$\downarrow$ to be corrected. Traverses were fairly equally divided up into daytime and nightime operations, and all were conducted under clear weather conditions ($<$ 1/8 cloud). Variables measured on the mobile traverses are included in Table 2. 1.

Two types of traverse were employed, one directional and two directional, depending on the availability of a second motorcar. Most traverses were of the one directional type using one motorcar and set of instruments over a route between the two fixed climate stations (Figure 2. 1). These occupied most of the late summer and early winter period of this study. Actual sites are indicated in Figure 2. 1 and are listed in detail in Appendix 1.

The two directional traverses gave a better spatial coverage of the city but were limited because of expense and the difficulty in obtaining another

TABLE 2.1

Variables Measured in this Study

FIXED SITES

(1) Total incoming solar radiation

(2) Diffuse solar radiation

(3) Incoming long wave radiation

(4) Smoke levels

(5) Temperature

(6) Vapour pressure

In addition at the airport

(1) Wind speed

(2) Wind direction

(3) Cloud amount

(4) Upper air temperatures

(5) Air pressure

MOBILE TRAVERSES

(1) Total incoming solar radiation

(2) Diffuse solar radiation

(3) Incoming long wave radiation

(4) Temperature

(5) Vapour pressure

(6) Relative wind speed (expressed verbally)

(7) Wind direction (obtained from smoke drift)

(8) Smoke levels (taken from nearest monitoring station)

motorcar. Dr I. F. Owens and Mr P. Tyree of the Geography Department were each able to help on occasions towards the end of the study period in June 1976. These traverses involved two vehicles and their instruments following routes from rural areas, crossing one another near the centre of the city and then continuing out to rural areas. The route was then retraced, stopping at each site in the same position on the road as on the outward trip. The routes followed are shown in Figure 2. 1. One vehicle travelled from Islington to the west of the city,to New Brighton in the east; the other vehicle travelled from McLean's Island to the northwest of the city, to the Sign of the Kiwi on the Port Hills to the south of the city. The sites employed in both directions are listed in detail in Appendix 1.

Figure 2. 1 shows that these traverses cover the whole range of land use types and are therefore representative of a complete urban/rural trend. The traverses have an added advantage in that they include other than urban climatic effects. The marine influence of the sea is felt to the east of the city and the effect of the hills is felt to the south of the city.

INSTRUMENTATION

The long term measurement of radiation requires two things in relation to instrumentation; durability under all conditions, and accuracy. Instrumentation used in this study generally satisfied both requirements. Portability of instruments was also a requirement for the mobile traverses. As this study investigates the variation of radiation in response to other atmospheric variables, it is therefore possible to divide instrumentation up into radiation and non-radiation recording instruments.

Radiation Instrumentation

Fixed Site

At the two fixed sites $LW\downarrow$ was measured using C. S. I. R. O. net radiometers which measure the balance between incoming all-wave radiation from above and below. The radiometers were adapted for the measurement of $LW\downarrow$ by attaching a black body cavity to the lower side of the instrument (see foreground instrument in Plate 2.1). The black body cavity contained a silicone diode temperature sensor which measured the radiating temperature of the inner surface.

After calculating LW↑ using the Stefan Boltzmann equation,

$$E = \epsilon \sigma T^4 \qquad \ldots. (2.1)$$

where E = flux of radiant energy

σ = Stefan Boltzmann's constant

T = surface temperature.

LW↓ was given by the following equations:

Nightime LW↓ = Rn + LW↑ .... (2.2)

Daytime LW↓ = Rn + LW↑ - SW↓ + SW↑ .... (2.3)

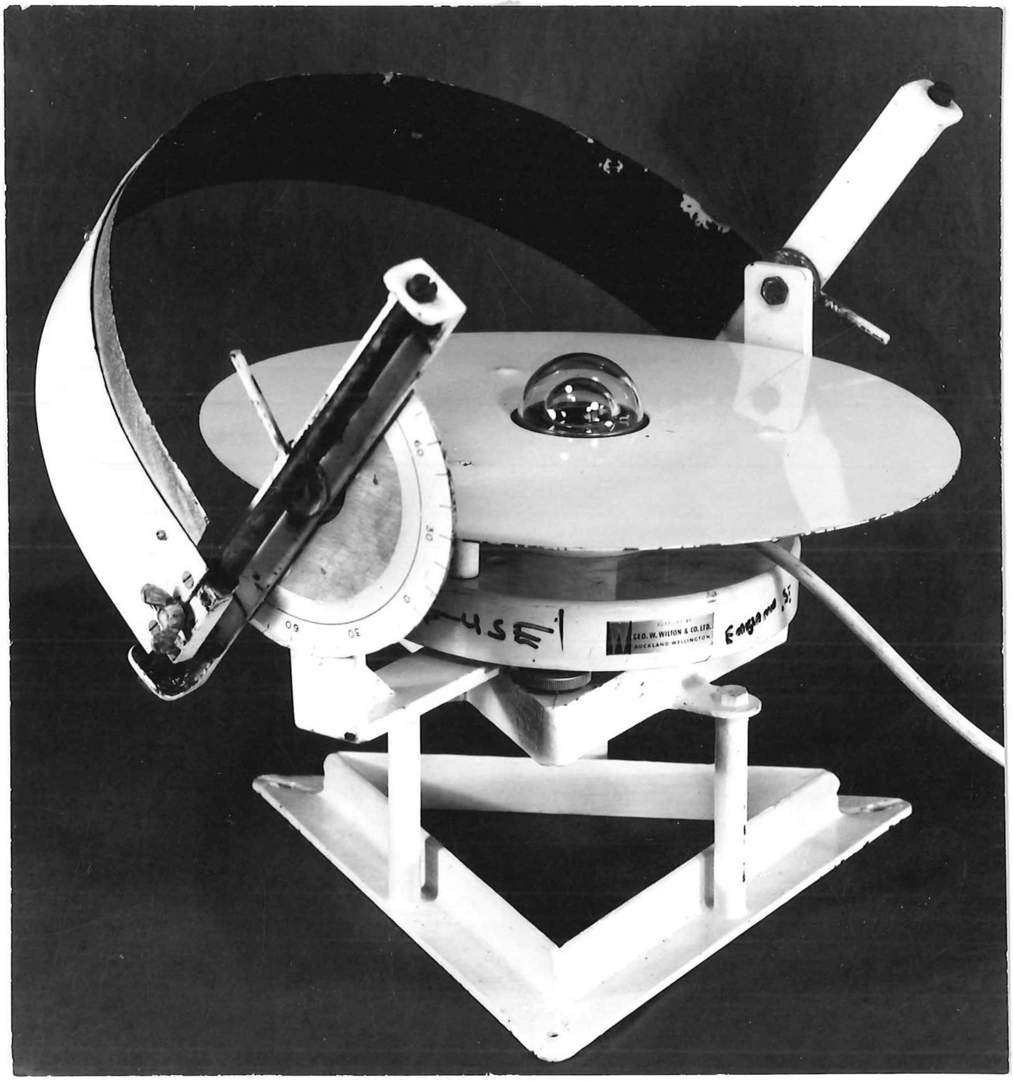
Manufacturer's calibration coefficients were applied to convert from readings in millivolts to the energy units used in this thesis (W/m^2).

Plate 2.2 shows the sensor for LW↓ at the rural site, along with the housing of the electric pump used to maintain polythene hemisphere inflation.

Solarimeters used at both sites were Kipp and Zonen CM5 models which are suitable for outdoor installation. The Meteorological Service's solarimeter at the rural site was an Eppley 16 junction differential thermopile model. One solarimeter at each site was employed using a shadow ring designed and manufactured within the Geography Department. The purpose of this device was to shield the sensor of the solarimeter from direct beam radiation, thereby measuring only diffuse sky radiation. Plate 2.3 shows the shadow ring with a solarimeter mounted within it.

A shadow ring is adjusted for its site in two ways. The latitude of the site (Christchurch 43° 30') is set by altering the angle that the ring makes with the horizontal plate of the solarimeter. The declination of the sun is adjusted for by moving the ring up and down its slide according

Plate 2.3 Shadow Ring with Solarimeter.



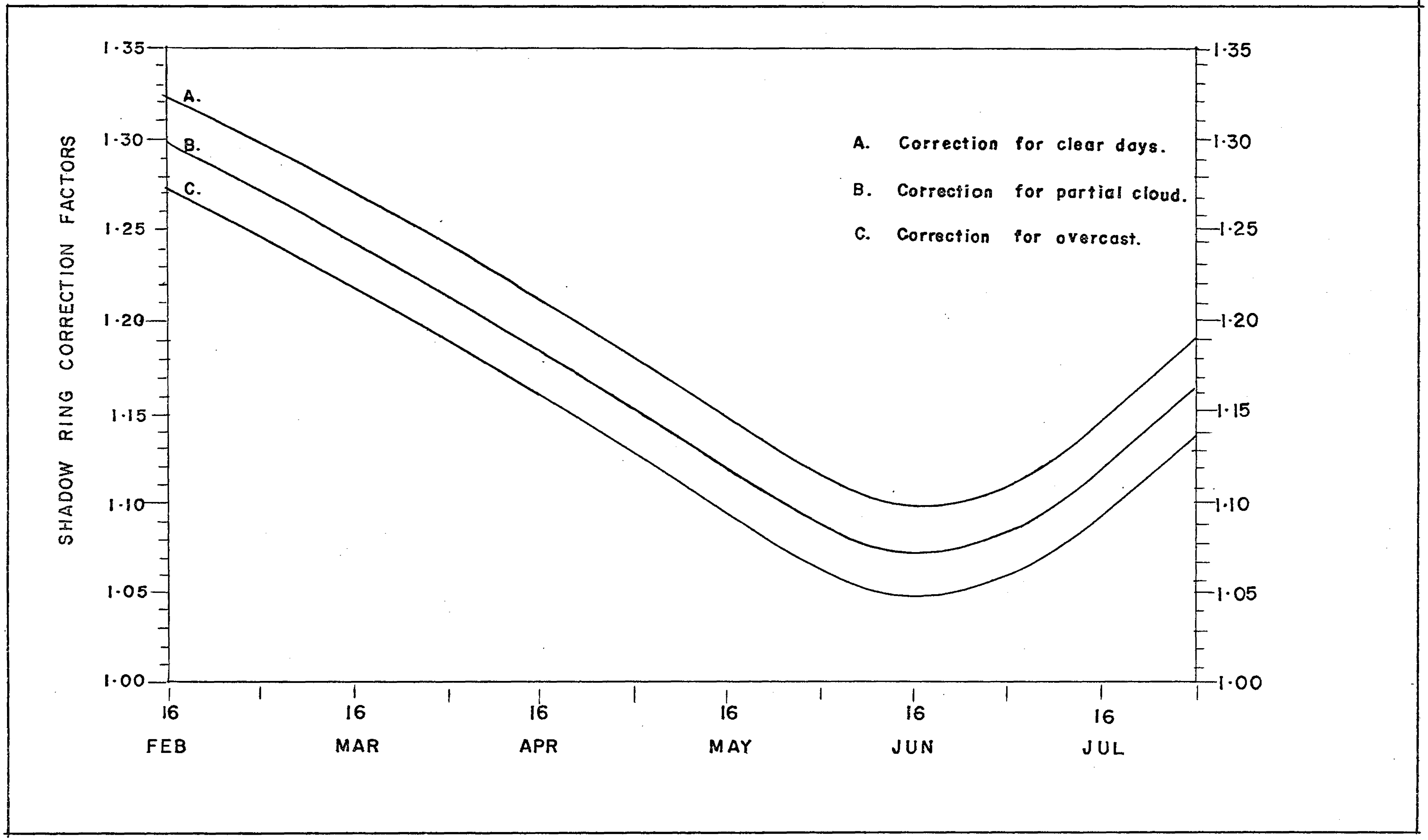
GEO. W. WILTON & CO. LTD.
AUCKLAND WELLINGTON

to the time of the year. During this study it was found necessary to alter the shadow ring once every three days to ensure that a shadow was always cast upon the sensor. The ring was 66.6 mm wide and the radius of the shadow ring was 190.5 mm.

One adjustment that must be made to the raw data is the application of a shadow ring correction for the diffuse component of solar radiation. Diffuse radiation is the energy component which is scattered out of the solar beam and diffused downwards by gaseous molecules, water droplets and solid particles. A contribution to the radiation from cloudless portions of the sky is also provided by the reflection of sunlight at the surfaces of cloud masses. The loss of radiation due to the presence of a shadow ring across the sun has been the subject of some discussion in the literature (Stagg, 1950; Blackwell, 1954; Drummond, 1955). This study follows the work done by Drummond for the calculation of shadow ring corrections for South Africa. Initial assumptions include isotropic diffuse radiation, a non-reflective receiving surface of the solarimeter, and zero back reflection from the inside of the shadow ring. Drummond's equation for shadow ring correction uses as inputs the width and radius of the shadow ring, the latitude of the site and the solar declination and was applied using the computer programme "SHADCORN" as listed in Appendix IV. The printout lists for an isotropic, cloudless and overcast sky and the latter two can be interpolated for a partly cloudy sky. Figure 2.2. shows shadow ring corrections made according to solar declinations for Christchurch's latitude. The graph is drawn so that four day averages can be extracted. It can be seen that using this method gives the highest correction factors during the summer and in clear skies.

All radiation sensory equipment had to be oriented towards true solar north and completely levelled. This was accomplished by using adjustable platform at both sites. Plates 2.1 and 2.2 show these wooden platforms.

Figure 2. 2 Shadow Ring Corrections for Christchurch


SHADOW RING CORRECTION FACTORS
1·35
1·30
1·25
1·20
1·15
1·10
1·05
1·00
A.
B.
C.
A. Correction for clear days.
B. Correction for partial cloud.
C. Correction for overcast.
16 FEB
16 MAR
16 APR
16 MAY
16 JUN
16 JUL

Signals from all of these transducers were recorded automatically; at the urban site on an Integrating Millivoltmeter System 601 and at the rural site on a Honeywell Electronik 194 2 channel, and a Toa Electronics single channel potentiometric recorder. Four of the six recording points on the integrator were utilised for total solar radiation, diffuse radiation, incoming all-wave radiation and black body temperature. Printouts for all channels were obtained hourly and the count of the machine could be varied according to the accuracy required or the individual output from each sensor. At the rural site all-wave and diffuse radiation were recorded on the Honeywell, while black body temperature was recorded on the Toa. The charts from these recorders had to be analysed manually while the printout from the integrator was already integrated over the hour.

Traverses

Instrumentation on the traverses was similar to that at the fixed site. LW$\downarrow$ was measured in the same way except that the LW$\uparrow$ value in the net radiometer was held at a constant $0^{\circ}C$ by having the "black body" cavity immersed in a bath of ice. Air flow to the polythene dome was supplied by a hand operated pump and when a two directional traverse was employed, an inflated truck tyre with an adjustable valve was used in the second vehicle. SW$\downarrow$ was measured using a C. S. I. R. O. albedometer and when a second instrument was required for use in a two directional traverse, a solarimeter was removed from the rural shadow ring. Diffuse radiation was obtained by the simple method of placing a hand between the sensor and the sun so that a shadow was cast across the sensor.

Recording of the output from the radiation sensors was obtained using a battery powered millivoltmeter which had a 5 mv and 50 mv full scan potential. The radiation sensors were all levelled manually by sighting through the horizon. An attachment was designed for each vehicle so that radiation recording sensors and the air pump could be outside the vehicle at all times, and this was equipped with a light for nightime work. Plate 2.4 shows the instrumentation used for the mobile traverses, including the radiometer, solarimeter, millivoltmeter, hand pump and sling psychrometer.

Calibration of Radiation Sensors

In order to obtain as much accuracy as possible in this study, a long calibration period was set up for the radiation instrumentation for the two fixed sites. The calibration took place at the airport over a period of two weeks from 17 January 1976 and included total SW↓, diffuse beam radiation and incoming LW↓ for the instruments from the two sites. Calibration was over 20 minute periods over the full day, and recorders used were the same as for the full study period.

The most careful calibration was between the Eppley solarimeter of the Meteorological Service and the Kipp and Zonen solarimeter of the Geography Department, both of which were to provide total SW↓ data for the respective sites. All equipment was set up 5 metres apart and at the same height.

A summary of the regression analysis carried out during the calibration period is shown in Table 2.2. Correlation for both total and diffuse SW↓ is high, with the rural SW↓ radiation levels having to be adjusted upwards in both cases. It was recognised that errors are likely to be greatest at low energy values (low sun angles). The correlation for LW↓ was lower than for SW↓, probably as a result of the more complex method of obtaining it. In the case of LW↓ the rural values had to be adjusted downwards.

The calibration of traverse radiation instruments was less exacting. All four instruments were operated adjacent to the urban recording station over a two day period of clear weather (traverses were predominantly undertaken under clear skies). Deviations of these instruments

Plate 2.4 Mobile Traverse Instrumentation. Showing radiometer, solarimeter, millivoltmeter, air pump and psychrometer.

TABLE 2.2

Summary of Calibrations

Sensor (X variable first)	a	b	r^2	N
Rural SW↓ (Eppley) + Urban SW↓ (KZ 721313)	39.90	0.970	98	204
Rural Diffuse SW↓ (KZ 721340) + Urban Diffuse SW↓ (KZ 721359)	7.7509	0.940	99	135
Rural LW↓ (CSIRO 6924) + Urban LW↓ (CSIRO 9616)	-68.2157	1.156	72	172

TABLE 2.3

Traverse Instrumentation Correction Factors

Instrument Use	Instrument	Correction
1 and 2 directional traverse	Albedometer	+14.3 w/m^2
	Radiometer (6918)	-18.0 w/m^2
2 directional traverse only	Solarimeter (721340)	+12.0 w/m^2
	Radiometer (6917)	-22.2 w/m^2

away from the urban site's instruments were averaged and then applied as a constant correction factor. Table 2. 3 shows the correction factor for each instrument.

Estimation of Error

An attempt has been made to estimate the likely errors in measurement of SW↓ and LW↓ at the permanent stations. Errors involved in other areas of this study will be discussed as they arise. Two simplifying assumptions have been made in the calculation of possible errors between instruments at the two sites. The first assumption is that the calibration period which was used for the estimation of errors was representative of the long term study. In actual fact the same standard error of estimate (S. E. E.) represents a far larger relative error in the winter than in the summer when calibration took place. (S. E. E. is the standard deviation about a line of average relationship and is a measure of the accuracy of estimates.) This fault may be partially corrected for in that this study concentrates on clear days (relatively higher energy values), whereas all weather data was included in the calibration period. The second assumption here is that individual instrumental error is included within the S. E. E. of the calibration regression equations. Further assumptions are made in the actual computations of error and these are listed in Appendix III.

Estimates of percentage errors in the values of the incoming energy components have been made using the above assumption and in the manner shown in Appendix III. Table 2. 4 shows the computed SW↓ and LW↓ errors over the various time periods calculated on the principle of Brooks and Carruthers outlined in Stanhill (1965). It can be seen that the calculation of LW↓ is subject to greater error than the calculation of SW↓ . This is due to the part that SW↓ plays in computation of LW↓ , therefore error in SW↓ is included in the LW↓ error.

TABLE 2.4

Estimated Percentage Errors in Values of Incoming Energy Components

Time Period	SW↓	LW↓
Day	6	9.5
Month	1	1.7
Year	0.3	0.5

Non-Radiation Instrumentation

Fixed Site

Humidity and temperature at the urban site was recorded on a Kohari thermohygrograph (humidity 0 - 100%, temperature -15°C to +40°C) which recorded a pen and ink trace on paper charts. This data was converted into vapour pressure using computer programme "HUMID" listed in Appendix IV. This instrument was calibrated against the rural temperature and humidity readings at the beginning of the study period. Smoke levels were recorded at the urban site from early March using a Research Appliance Company A. I. S. I. sampler model F. 2. This instrument utilised a timer and continuous paper tape to monitor two hourly smoke concentrations in phase with the integrator printout of radiation values. The through flow of air could be adjusted according to relative atmospheric contamination, and in this study the flow rate was halved during April as smoke levels began to increase.

The paper tape was analysed using a D. S. L. Smoke Stain Reflectometer which directs a light source at a specimen stain and records reflected light at a photocell which is coupled to a sensitive microammeter. The reflectance is converted to a smoke concentration in ug/m^3 using a chart and adjusting for flow rate. Smoke was used in this study in lieu of other pollutants for two main reasons; the ease of its measurement, and the well documented effect that smoke has in modifying radiation transfers. It is described in the literature as being one of the most efficient attenuators of radiation (Hand, 1943; Sanderson _et al._, 1973; Emslie, 1964; East, 1968) and it is also a reasonable indicator of variations of other pollutants (given that the meteorological conditions favourable to smoke pollution are the same as those for other pollutants). A direct measure of smoke pollution is still a better measurement than coefficient of haze (C. O. H.), which many other workers in this field have used.

Non-radiation meteorological parameters at the airport were obtained from Meteorological Service records. Temperature and humidity readings from standard wet and dry bulb thermometers were extracted hourly as was wind speed, using a standard British Meteorological Office 3 cup anemometer connected to a Munro Electric Anemograph. Upper air data on temperature was obtained from N. Z. M. S. radiosonde soundings using balloon and radar. Over the period of this study one flight each day was made. Twenty-four hour smoke concentrationsfor the rural site were obtained using a locally built version of the Research Appliance Company sampler, and this was set to change stains at 0000 hrs true solar time.

Mobile Traverses

Temperatures and humidity on the traverses were taken using either a whirling sling psychrometer or an Assman aspirated psychrometer which were found to be similar in response. Wind speed was expressed verbally within the terms of calm, very light, light, moderate and fresh, while wind direction was obtained from a lit match. This system, although not particularly accurate, was considered reasonable in the terms of this study. Smoke levels at each site on the traverse were taken from the nearest Health Department pollution monitoring station and were either of the 2 hour or 24 hour type.

TESTS OF SITE REPRESENTATIVENESS

View Factors

An important consideration in a study such as this is the representativeness of radiation measuring sites used one to another. Complete similarity is an impossibility, hence possible limitations should be accepted and accounted for. The greatest variation between sites in this study was in view factor, an index of the proportion of unobstructed sky out of the total hemisphere in view to the radiation sensor. View factors are easily obtained by plotting obstructions on polar graphs using grids for determination of total area covered. View factors have two important effects on incoming radiation. With SW↓, obstructions can directly interfere with the solar beam, while an obstruction of sky for LW↓ has the effect of warmer objects blocking out the lower radiating sky.

Tables of view factors for each site used in this study are shown in Appendix I. View factors range from 98% for rural sites down to 75% for some urban sites. These limitations are discussed in relation to the mobile traverse data in the relevant chapter. Of importance here is the representativeness of the two permanent radiation sites at the airport and England Street. The difference in view factors is negligible, 97.0% and 96.7% respectively. As important as the proportion of sky covered, is the part of the sky obstructed, particularly with regard to SW↓ . Figure 2.3 shows solar paths and the part of sky obstructed for the urban and rural sites. At neither site do obstructions exceed 15^{o} elevation or directly block the solar beam at times of low sun angles. The two sites are considered representative enough for direct comparisons to be made without recourse to corrections for view factor.

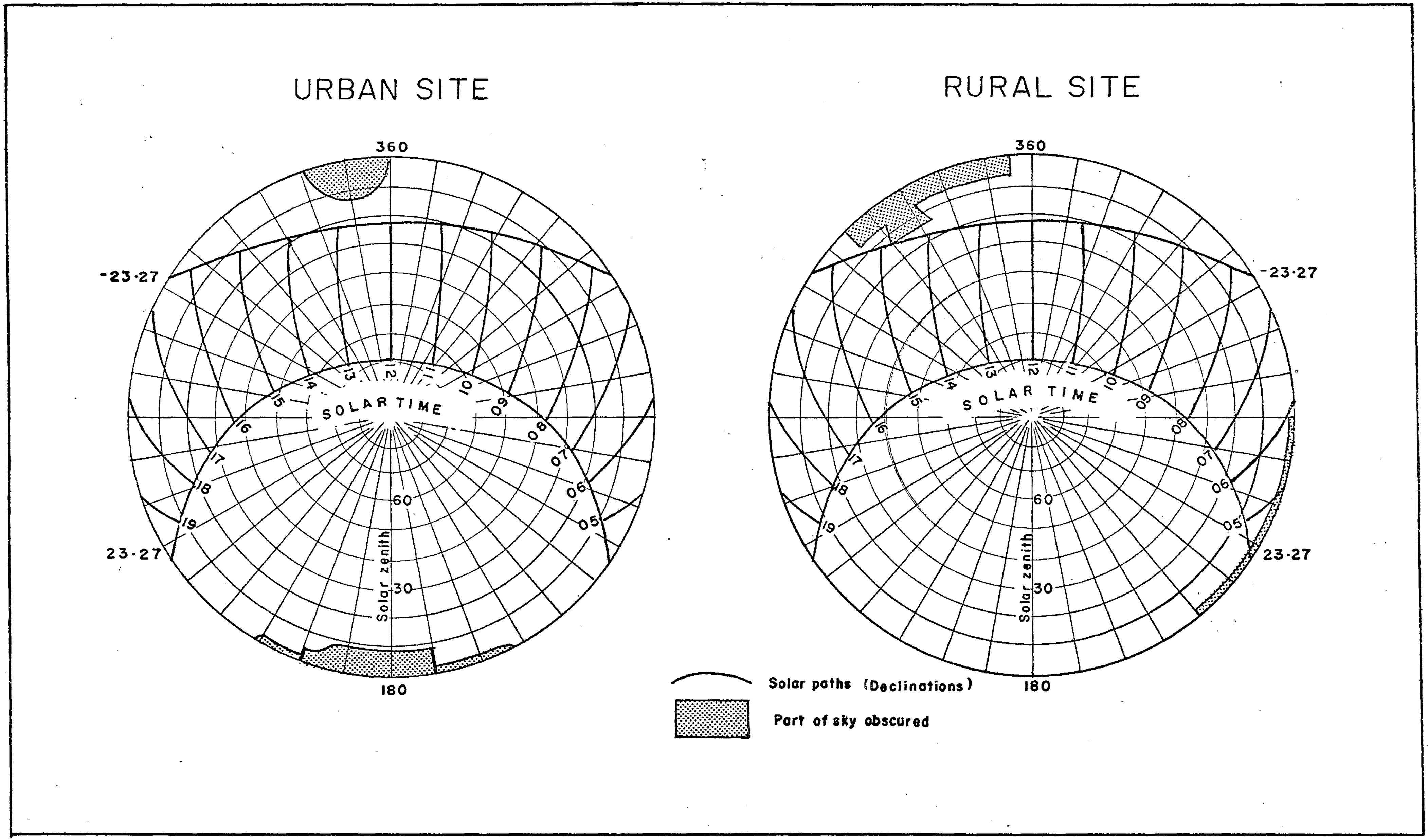
Long Term Urban Effects on Airport Radiation

One other factor which could inhibit a true urban/rural comparison of radiation trends in this study is the possible urban effect on the chosen

Figure 2. 3 Solar Path and Horizon Diagrams:

a) Rural Site

b) Urban Site


URBAN SITE
RURAL SITE
360
180
-23·27
23·27
SOLAR TIME
05
06
07
08
09
10
11
12
13
14
15
16
17
18
19
60
30
Solar zenith
Solar paths (Declinations)
Part of sky obscured

rural site. An examination of 15 year seasonal radiation trends (1960-1974) as measured at the airport, reveals a trend which may represent an increasing urban effect through high level pollution or some other atmospheric variable. The following analysis examines the significance of the slope of the radiation regression line for Christchurch Airport, compares the trend with sunshine and also compares the trend with a similar analysis done for Wellington radiation data. The data used is percent of radiation or sunshine out of a maximum possible for each of the four seasons of the year. The total data base is therefore near 60 observations.

The initial test was one of the significance of the slope of the regression line away from zero over time (no radiation change over time). The method used is adapted from Krumbein and Graybill (1965). The null hypothesis is

$\hat{b} = b_o$ (no change), and is rejected if $v \geqslant t(n - z)$

where t = t statistic

$v = \chi (b - b_o)$

χ = root corrected sums of x^2

Table 2. 5 shows the summary of regression and the results of the test for the significance of the slope of the b coefficient.

Two potentially very interesting pieces of information arise from this analysis. Firstly, the trend towards a decreasing $SW\downarrow$ at Christchurch Airport is a very strong one ($r = -0.7085$), and is statistically significant. The trend does not show for Wellington where the same general trend would be expected to show up in the event of an overall climatic variation. Secondly, and supporting the above observations, is the fact that Christchurch sunshine deviation shows no trend whatsoever, contrary to what would be expected. The following relationship between $SW\downarrow$ and sunshine has been well established in the past (Chang, 1971):

TABLE 2.5

Regression Analysis with Time as Independent Variable

Dependent Variable	a	b	r	Signif. of b	d.f.
Christchurch SW↓	54.109	-0.1662	-0.7085	0.001	57
Christchurch Sunshine Duration	46.556	0.008904	0.0358	N.S.	57
Wellington SW↓	47.371	0.046929	0.2073	N.S.	57

$$Q/Q_A = a + b\,(n/N) \qquad \ldots. \; (2.4)$$

where, Q is global radiation, Q_A is radiation outside the atmosphere, n is actual duration of sunshine, N is maximum possible sunshine, and a and b are constants.

Therefore for any observation of percentage received radiation, there should be a direct relationship with percentage received sunshine holding all other factors constant.

There seems to be only one feasible explanation of the apparent decrease in radiation received with no change in sunshine amount, and that is a decrease in radiation intensity as a result of some atmospheric factor. A decreased radiation intensity would not necessarily affect the sunshine recorder, as above 0.3 langley/minute a Campbell-Stokes recorder will continue to burn. However, measured radiation does record changes in intensity.

It is difficult to define the exact reason for this inferred decrease in atmospheric transmissivity to $SW\downarrow$, but the lack of a similar trend in Wellington tends to rule out most meteorological factors such as increased water vapour, unless they were very localised. In the absence of further information it appears likely that the reason for the decreased radiation is related to the encroachment of Christchurch city on to surrounding rural lands and towards the airport. Despite the low smoke levels still, there is evidence that smoke levels at ground level at the airport have increased up to 100% over levels of 15 years ago (Chapter 3), although some of this is probably due to increased air traffic. However, it is pollution at higher levels which is probably responsible for the trend described.

As a check on the analysis performed, the confidence intervals on the b coefficient for both Christchurch and Wellington were checked at the strict level of .001. If the difference between the b coefficient of both sites is significant, then $(b \pm C.I.)_{Well.}$ will not overlap $(b \pm C.I.)_{ChCh}$. The method of computation is outlined in Krumbein and Graybill (1965).

$$\text{Confidence Interval (C. I.)} = \frac{1}{\mathcal{X}} \left(t^{.001} (n - z)\right)$$

where $\mathcal{X}$ = root corrected series of x^2

t = t statistic.

The resultant confidence interval for the Christchurch data b coefficient was -0.24207 to -0.09031 (b = -0.16621), and that for Wellington was -0.0645 to +0.1484 (b = 0.04693). These confidence intervals therefore do not overlap at the .001 level of significance.

Assuming that the above trend is due to an urban effect on the airport's incoming radiation, then any differences found in radiation between the two sites may be an underestimate of the maximum possible urban/rural difference. Whatever the reason for the trend in SW$\downarrow$ at Christchurch Airport, the subject is worthy of much further analysis than is possible in this thesis.

DATA COLLECTION PROGRAMME

The equipment was established and running from 24 February through until 4 July 1976. Equipment was not run continuously for several reasons. Firstly, the long term stations required daily inspection and this was not possible over the entire period. Secondly, it was uneconomic, especially with the chart recorders, to have them running continuously. Thirdly, where the weather was unsuitable the equipment was also shut down. All of these considerations gave rise to the discontinuous nature of the recording period outlined in Appendix II. This also gives the dates and nature of the mobile traverses which were largely dependent on the occurrence of clear weather.

METHODS OF DATA ANALYSIS

The major analytical emphasis in this thesis is empirical in nature, and as a consequence of the aims, the analysis involving statistical data was of two types. Firstly, tests were made for differences in radiation parameters between urban and rural sites using standard statistical parametric tests such as the t-test. Secondly, tests were made for relationships between variables using simple linear regression and multiple regression. These tests were carried out on the Geography Department's mini-computer and the programmes used were adaptations of the package programmes provided by the machine's manufacturers.

Some of the data was not amenable to statistical analysis, particularly that derived from mobile traverses. In this case analysis was restricted to graphical or map presentation.

An empirical approach to the investigation of the effect of other variables on urban/rural radiation differences is restricted as regards the establishment of cause and effect. In such cases use was made of theoretical analysis based on physical processes to attempt to establish possible mechanisms underlying statistical correlations.

CHAPTER THREE

BACKGROUND TO STUDY AREA AND URBAN/ RURAL DIFFERENCES IN ATMOSPHERIC VARIABLES

INTRODUCTION

This chapter produces a background for the rest of this thesis by describing firstly the general locational, climatic and air pollution characteristics of Christchurch, and then more specifically by describing the characteristics of various atmospheric parameters for 1976. The overall aim is to provide background information relating to factors which could potentially influence SW$\downarrow$ and LW$\downarrow$ across Christchurch. While there are overlaps, these variables appear to fall into three groups:

i) Pollutants,

ii) Meteorological factors influencing pollutant levels,

iii) Meteorological factors influencing LW$\downarrow$ and SW$\downarrow$ directly.

These three groups are discussed with special reference to urban/rural variations, as well as variations over time. Variables which fit into the second two categories include wind speed and direction, atmospheric mixing depths, temperature and atmospheric vapour pressure.

DESCRIPTION OF STUDY AREA

Location and General Characteristics

Christchurch city lies on the east coast of the South Island of New Zealand at latitude 43° 30' S, 172° 40' E. The urban area is about 10-15 km in diameter (Figure 2. 1) and the population is near 300,000. As a result building densities are low, with most dwellings being single story detached houses. The central business district has an area of 1-2 km in diameter with buildings mainly 25-35 metres tall. A large park (3 sq. km.) lies immediately to the west of the city centre and two minor rivers meander across the city draining into a large estuary to the south east of the urban area.

The city is situated on the low lying and alluvial gravel Canterbury Plains and is therefore mainly flat or gently sloping. The ground rises from the sea, 8 km from the city centre, to 20 metres at the northwest of the urban fringe. From this point the Plains continue to slope gently upwards towards the west, reaching an altitude of 300 metres within 40 km of the city. Beyond this point, ground rises steeply to over 2000 metres in the eastern foothills of the Southern Alps. Five km to the south of the city centre the Port Hills rise steeply to 500 metres. There are no major topographic obstructions for 50 km to the north of the city.

General Climate of Christchurch

The area lies between the subtropical anticyclones and the disturbed mid-latitude westerlies. Mean winds at undisturbed levels are therefore westerlies, but because of large scale topography winds below 1000 metres usually have a northeast or southwest component. The synoptic scale weather of the area is dominated by a regular procession of eastward moving anticyclones, with a recurrence interval of one week to ten days (de Lisle, 1969). Anticyclones have a trough between them which usually contains a cold front, therefore conditions of stagnant weather do not last very long.

Another dominant control upon the climate of Christchurch is the barrier of the Southern Alps to the west, which affect the climate of the city in a number of ways. Föhn wind effects are a frequent occurrence, particularly in the spring and autumn (Lamb, 1970). The Alps sometimes retard the passage of cold fronts and create low pressures to the lee of the mountains over the Canterbury Plains (Sevelle, 1969). Christchurch's comparatively low rainfall can also be attributed to the rainshadow effect of the Alps acting on the dominant westerly flow.

With westerly flows at undisturbed levels and high mountains upwind, skies are frequently clear. This promotes strong night cooling with frequent nocturnal inversions, especially in winter anticyclonic conditions.

Katabatic wind flows (downslope drainage of cold air), are readily established both off the plains and foothills to the northwest and off the Port Hills to the south. On nights of light winds (frequent in winter), because the city is flat, air from the two katabatic sources "ponds" up in the area (Ryan, 1975).

Characteristic features of Christchurch's climate are endorsed by comparison with other New Zealand centres. Table 3.1 shows that Christchurch has a lower rainfall, fewer rain days and a greater temperature range than the other cities. The most important feature of Table 3.2 is the high percentage of possible sunshine for Christchurch in winter, this lack of cloud helping with promotion of inversions. Table 3.3 indicates the sheltering effect of the Alps, especially in the warmer seasons when the northwesterly wind is blowing. Humidity as low as 5% can occur at such times. Table 3.4 shows the windiness for the four main centres, the most important point being the lack of strong winds in Christchurch in the wintertime. Calms occur 20% of the time and are more frequent in winter than in summer. Calms are a factor in determining the high pollution potential of Christchurch. While the characteristics of the Christchurch climate can be contrasted to a certain degree with other New Zealand urban areas, it should be remembered that New Zealand as a whole is characterized by high sunshine hours and high windiness, even when compared to other mid-latitude areas (Garnier, 1958).

From the above discussion it can be seen that Christchurch is ideally situated for the frequent occurrence of conditions conducive to high pollution potential in winter. However, even in winter the city is generally well ventilated, so that daytime pollution levels after about midday, when the nocturnal inversion has been destroyed by surface heating, are almost always low. It therefore follows that sources of nocturnal air pollution (domestic fires) have a more dominant effect than the size of emission would suggest.

TABLE 3.1

Climatological Averages

Station	Rain Days	Rainfall (mm)	Mean Temp.	Mean Daily Max.		Mean Daily Min.		Mean Ann.	
				Jan.	July	Jan.	July	Max.	Min.
Auckland	140	1268	15.3	23	14	16	8	27	3
Wellington	124	1271	12.4	20	11	13	5	26	1
Christchurch	85	658	11.4	21	10	12	1	32	-4
Dunedin	119	772	10.9	19	10	11	3	30	-2

TABLE 3.2

Sunshine % of Poss.

Station	Summer (%)	Winter (%)
Auckland	51	44
Wellington	52	42
Christchurch	46	45
Dunedin	41	43

TABLE 3.3

Humidity

Station	January		July	
	3 a.m.	3 p.m.	3 a.m.	3 p.m.
Auckland	85	63	90	74
Wellington	89	71	87	77
Christchurch	83	57	88	70

TABLE 3.4

Average Number of Days with Gusts Reaching 40 mph or more.

Station	Nov.-April	May-Oct.	Year
Auckland	20	28	48
Wellington	90	98	188
Christchurch	31	23	54
Dunedin	28	32	60

N. Z. Year Book, 1975.

ATMOSPHERIC POLLUTION IN CHRISTCHURCH

Background

The peculiar problems of air pollution in Christchurch were perceived early in the province's history. In a paper entitled "On the dissolved matter contained in rainwater collected at Lincoln, N. Z.", Gray (1910) measured amounts of up to 50 $\mu g/m^3$ per day, a figure which appears to be fairly close to current levels. In the 1930's Barwell and Farr (unpublished Report) on behalf of the Christchurch Sunlight League, made measurements on the precipitation of solid matter. Regular scientific studies were begun by the D. S. I. R. in the mid 1950's.

In February 1959 the Air Pollution Advisory Committee of the Christchurch Regional Planning Authority was established. A five year investigation of the problem began shortly after this, and culminated in the publication of a report of comprehensive results and recommendations in 1966. The Health Department in Christchurch continues an intensive monitoring programme on urban pollution, especially over the winter months. Regular reports are produced, the next of which is due to be published early in 1977.

The Present Situation

The principal pollutants in and around Christchurch can be divided into two classes; particulate and gaseous. Particulates include smoke, dust and grit; while gaseous pollutants include sulphur oxides, nitrogen oxides and carbon oxides. Any process in which fossil fuels are burned produces carbon dioxide and to a certain extent nitrogen oxides and carbon monoxide. Smoke is produced when combustion is incomplete, while dust and grit originate primarily from industrial boiler plants and are emitted in flue gases.

The sources of smoke in Christchurch in order of quantity produced are as follows:

a) the domestic open fire,

b) industrial combustion,

c) incinerators for the disposal of wood waste,

d) heavy trucks, buses and motor vehicles.

(Pullen, 1970)

Table 3.5 indicates fuel consumption and emissions of smoke from various sources within the city over the three winter months, for the 14 years to 1974. A decreasing coal usage for domestic purposes and an increase in the consumption of motor spirits and diesel oil, associated with the motor vehicle increase, is evident. These trends are reflected in the amount of smoke emitted from the various sources, with only industrial emission remaining relatively constant.

Along with emissions of smoke, smoke pollution levels in winter months from 1960-1974 show a definite decrease (Figure 3.1), which is paralleled by a decrease of sulphur oxides (both by-products of coal combustion). The general trend of decreasing particulates and sulphur oxides can be explained by:

a) changing domestic heating methods,

b) the use of coal of lower sulphur content (Kennedy et al., 1974).

Despite the decreases, domestic fires still contribute largely to winter pollution levels and the winter smoke concentrations (60-80 $\mu g/m^3$) are still relatively high by New Zealand standards. While smoke and sulphur oxides have decreased, recent measurements of nitrogen oxides suggest a slight increase in this pollutant (Figure 3.1).

Table 3.6 compares smoke levels 1963/64 and 1974/75 for different parts of the city. The trends confirm Figure 3.1 and show that the smoke reduction is greatest for the central city and inner suburban areas. "Rural" areas which include Islington, Huntsbury Hill and Harewood do not show this trend and actually seem to be receiving more pollution as the city expands.

Trends described above suggest that there may be some potential in Christchurch for development of a Los Angeles type smog, resulting from

TABLE 3.5

Fuel Consumption and Emissions Three Winter Months (Mid May - Mid August)

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
Fuel (thousands tons)																
Domestic Coal Usage			36.9			44.9	14.0	38.2	38.7	34.5	28.3	23.4	24.7	19.2	27.2	
Industrial Coal Usage			19.8			22.1	21.8	22.4	21.5	20.6	23.5	21.4	29.4	23.2	21.5	
Motor Spirits and Diesel Oil			17.8			21.3	23.2	24.4	26.4	28.2	30.4	31.2	31.3	32.4	33.3	
Smoke Emissions (tons)																
Domestic			1292			1572	1575	1337	1354	1207	990	819	864	672	850	
Industrial			198			221	218	224	215	206	235	214	294	232	215	
Motor Vehicles			57			68	75	78	100	110	123	122	104	96	109	
Domestic % of total			80			83	83	79	79	79	73	71	69	67	72	
Motor Vehicles % of total			3.5			4	4	5	6	7	9	11	8	10	9	
Industrial % of total			16.5			13	13	16	15	14	18	18	23	23	19	

Source: Health Department Data.

Figure 3.1 Annual Average Concentrations of Pollutants (Central City) 1960-76.

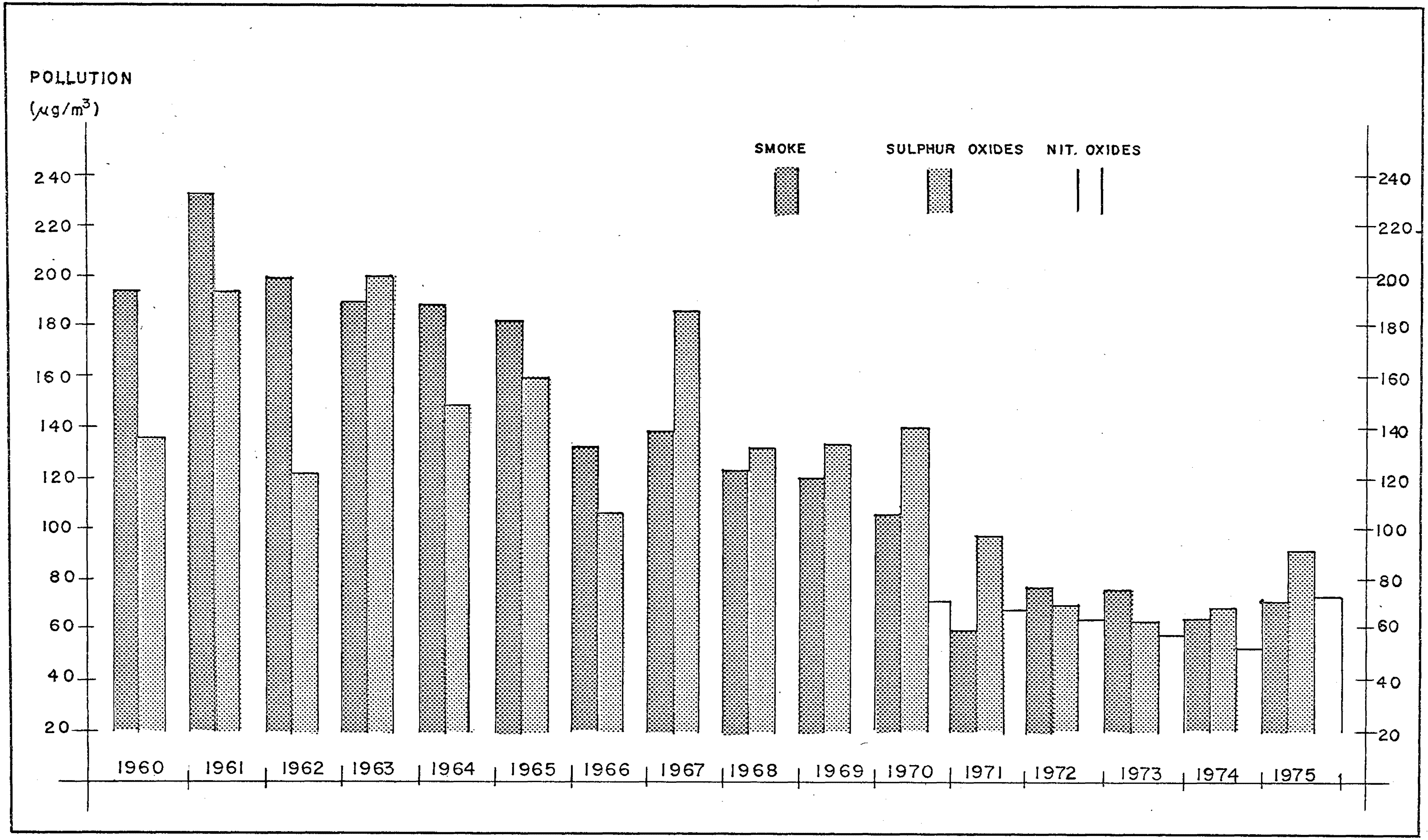

POLLUTION
(μg/m³)
SMOKE
SULPHUR OXIDES
NIT. OXIDES
240
220
200
180
160
140
120
100
80
60
40
20
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975

TABLE 3.6

Comparison of Smoke Levels June/July 1963/64 and 1974/75 ($\mu g/m^3$)

	Central City			Inner Suburban			Outer Suburban			Rural			Metropolitan Av.		
	63/64	74/65	% Redn	63/64	74/75	% Redn	63/64	74/75	% Redn	63/64	74/75	% Redn	63/64	74/75	% Redn
Average Smoke	106	73	29	130	98	25	74	67	9	13	20	-	89	70	21
% of readings greater than 120	31	19	39	40	28	30	24	17	29		Nil		26	18	31
% of readings greater than 250	9	2	78	12	8	33	3	3	-		Nil		6	4	32
Average of readings greater than 250	313	330	-	368	335	9	345	335	3		N/A		356	334	6

Source: Health Department Data

photochemical reactions between hydrocarbons, nitrogen oxides, ozone and oxygen in the presence of high intensity solar radiation.

Los Angeles is situated at a latitude where the incidence of solar radiation is relatively high and where there is little atmospheric smoke to absorb and reduce the intensity of incident ultra-violet light. London, although having higher relative emission rates of hydrocarbons and nitrogen oxides, does not experience a photochemical smog because of its higher latitude and high smoke emission rate.

Christchurch, while not to the same extent, has the potential for development of photochemical smog in summer and autumn, especially more recently with the relative increase of hydrocarbons and nitrogen oxides, at the expense of smoke. While there is not the same emission rate of reactant gases, nor is there a persistant subsidance inversion trapping these reactants, the total radiation intensity is not too far removed from that of Los Angeles. Summer half yearly seasonal solar radiation at the top of the atmosphere above Christchurch (43.5^{o}) is only 3.4% less than that above Los Angeles (34^{o})[1]. The 1966 Air Pollution Advisory Report states: "If the relative emission rates for Christchurch should, however, change materially and approach those obtaining in Los Angeles, it is conceivable that similar but less intense 'smog' episodes could occur here." It appears that such a situation may be being approached, as the dirty brown haze visible across the city on calm, late summer days would seem to testify.

This hypothesis may be able to be tested shortly with the introduction by the Health Department of continuous monitoring of ozone, nitrogen oxides and smoke, over the 1976-1977 summer. This information will be of use in describing any pollutant effects on radiation characteristics over the high sun period.

With the background to Christchurch atmospheric pollution discussed, the 1976 smoke data is examined in more detail for yearly, daily and spatial trends across the city.

1 - Source: Table 133, P. 415, Smithsonian Meteorological Tables.

Smoke Pollution During the Study Period

General levels of smoke pollution over the winter of 1976 appear to be similar to those of the immediate past four years. The June/July smoke concentration for the urban site (England Street), was an average $104\mu g/m^3$ as compared with $106\mu g/m^3$ in 1975. Days of $250\mu g/m^3$ are generally regarded as severely polluted, and these occurred on 8% of the days of the three months winter period. The World Health Organisation's recommendation is for 98% of observations each year to be below $120\mu g/m^3$. At the urban site in 1976 this amount was exceeded on 27% of winter days.

Table 3.7 shows monthly average smoke concentrations for the two sites, while daily variations are shown in Figure 3.2. Late summer shows little measurable difference between sites, the difference becoming greater towards winter. The highest daily average smoke measured was $406\mu g/m^3$ on 4 July at the urban site, while the highest recorded at the rural site was $79\mu g/m^3$ on 26 June. The average winter smoke amount at the airport of $20\mu g/m^3$ is higher than the only other smoke records kept there ($10\mu g/m^3$ in June/July 1963).

The seasonal trend in smoke pollution can be attributed to two factors; seasonal differences of climate, and of fuel usage. The importance of domestic emissions has been mentioned and it can be appreciated that in the summer season, emissions from this source are cut significantly. However, seasonal changes in climatic conditions, especially relating to dispersion, are an important consideration and are discussed later in this chapter.

Superimposed on seasonal trends are trends of smaller amplitude, such as synoptic or daily trends. Figure 3.2 illustrates this fact. Most peaks and troughs of smoke pollution are associated with the passage of weather systems. For example, the troughs in early June are associated with strong, warm, northwest winds which were effective in dispersing pollutants. This period was followed by calm, clear anticyclonic conditions which inhibited dispersion from about the 10 to 18 June, which again gave way to strong winds aiding dispersal of pollutants.

TABLE 3.7

Monthly Average Smoke Concentrations by Site ($\mu g/m^3$)

	March	April	May	June	July
Urban	4[x]	23	71	84	124
Rural	4[x]	7	13	18	21[x]

[x] Incomplete observation.

TABLE 3.8

Spatial Trends in Air Pollution 1976 (Smoke $\mu g/m^3$)

	A Reserve Bank	A Manchester Street	A Bealy Avenue	B Linwood (urban site)	B Avonside	C Shirley	C Fendalton	C Beckenham	C Bromley	D Harewood (rural site)
May	27	42	51	71	45		39	29	24	13
June	42	54	71	84	61		57	31	40	18
July	60	84	106	124	116	77	91	58	51	
Winter Average	43	60	76	93	74	77[1]	62	39	38	15[2]

A - central city B - inner suburbs C - suburban D - rural

1 - 1 month only 2 - 2 months only

Figure 3.2 Mean Daily Smoke Concentrations over 1976 Study Period at the Urban and Rural Sites

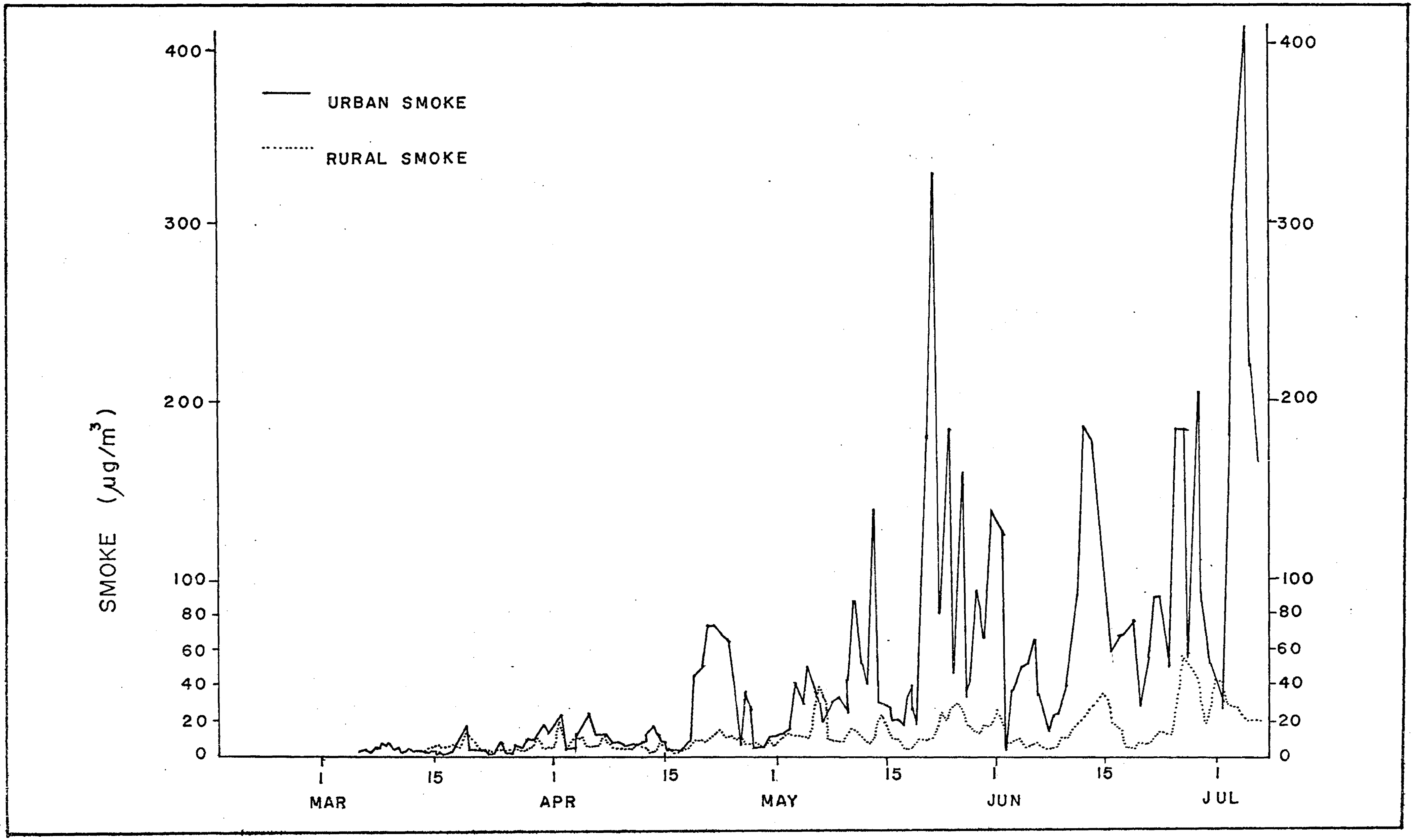
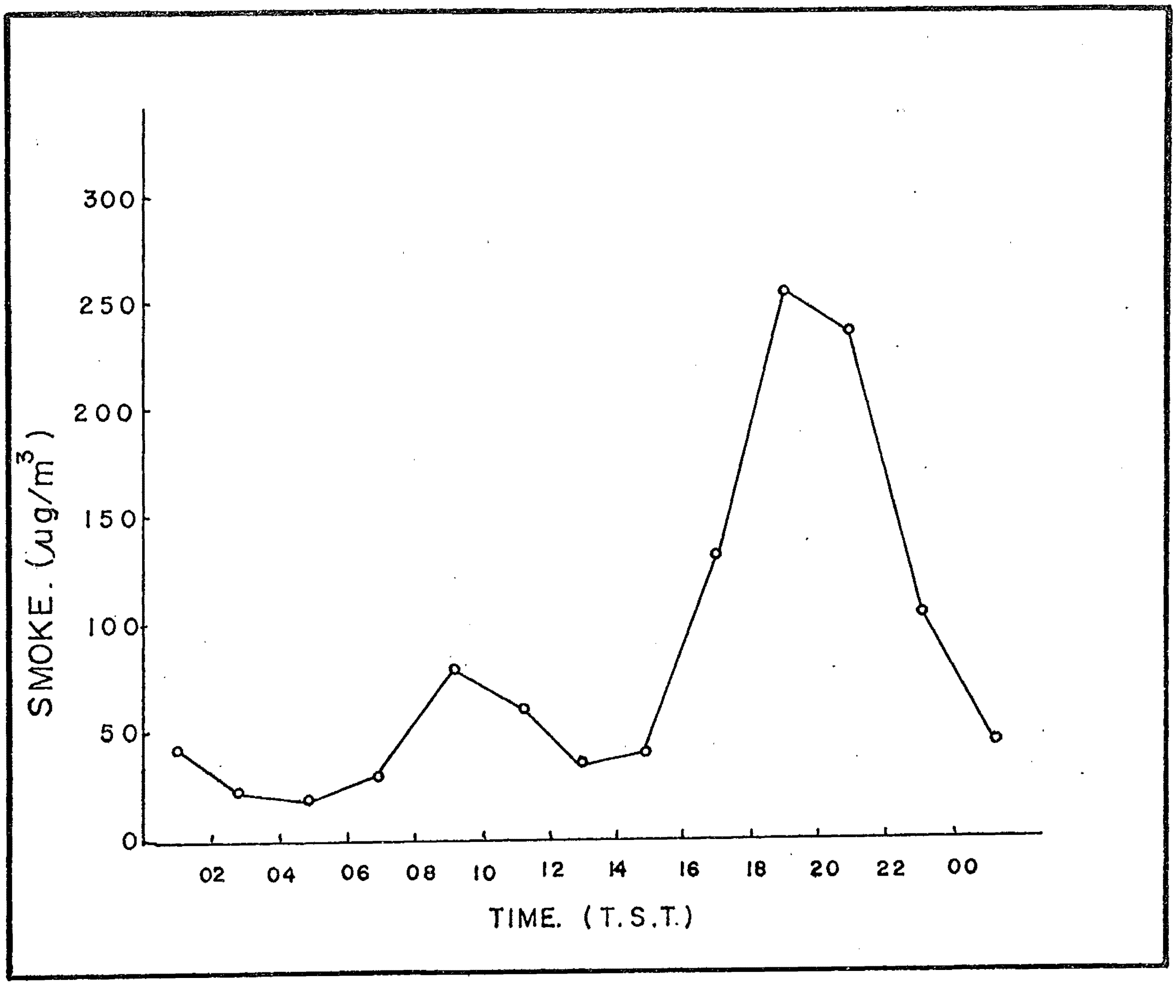

URBAN SMOKE
RURAL SMOKE
SMOKE ($\mu g/m^3$)
400
300
200
100
80
60
40
20
0
1
15
MAR
APR
MAY
JUN
JUL

Figure 3.3 shows the average daily variations in smoke concentration for June 1976 at the urban site. The most important features of this graph are the two smoke peaks, a small one of $80 \mu g/m^3$ at 0900 hrs and a much larger one of $253 \mu g/m^3$ at 1900 hrs. According to the Report of the Air Pollution Advisory Committee (1966), the reasons for these peaks are largely emission factors, but meteorological factors are also a consideration. In winter, on the frequent clear calm days, an overnight temperature inversion develops which inhibits dispersion, and from 0700 hrs pollution builds up as domestic fires are lit, traffic begins to move and industrial activity begins. By late morning the overnight temperature inversion breaks up in response to warming surface temperatures. In late afternoon the inversion redevelops and smoke pollution climbs in response to the lighting of domestic fires.

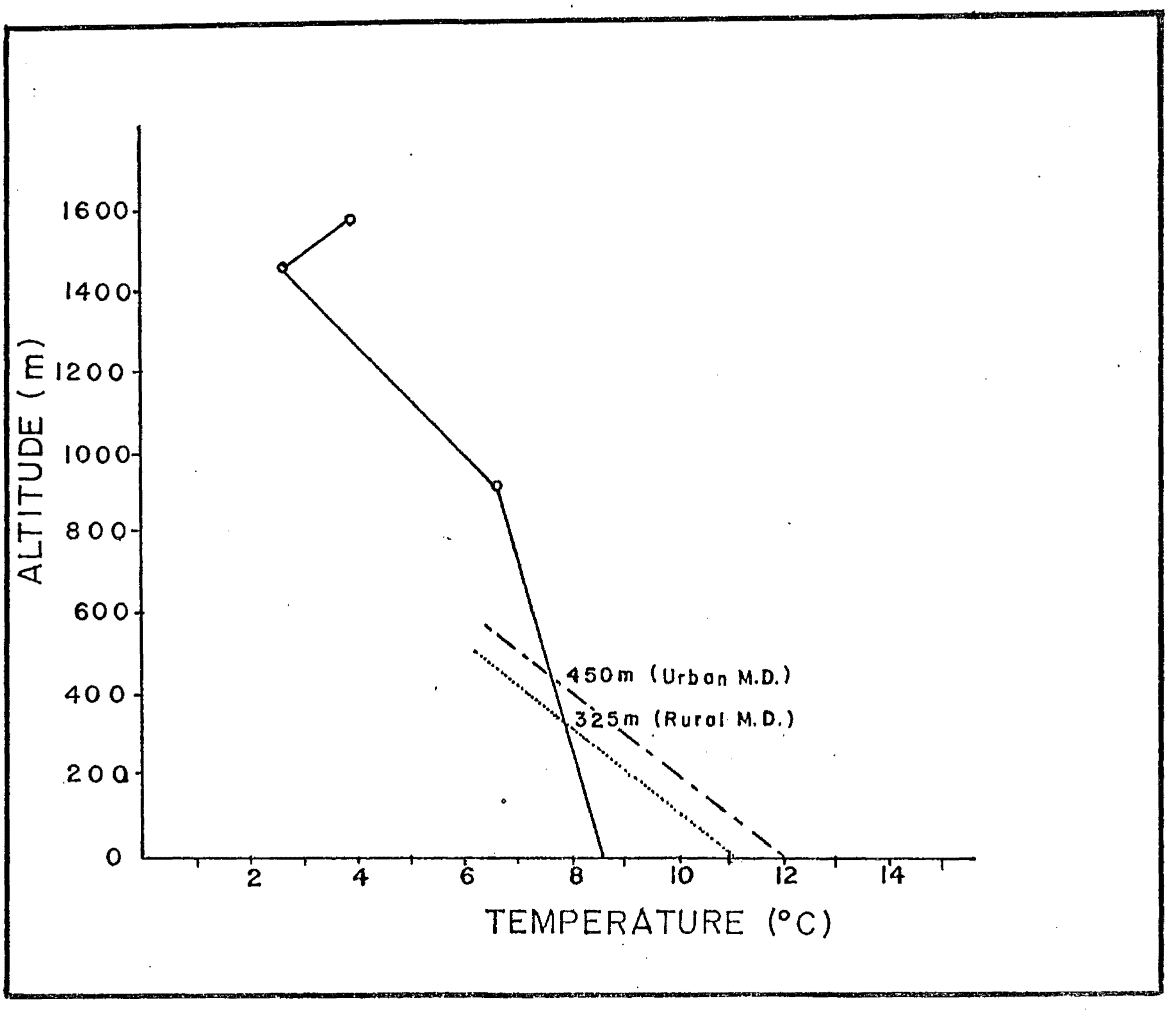
Table 3.8 shows spatial trends in smoke concentration evident over the three winter months in 1976 for ten monitoring sites across the Christchurch metropolitan area. This table indicates the position of the inner suburban areas of Christchurch as being the most polluted, this probably being due to the large number of older homes with open fires in these areas. From the inner suburban peak there is a drop in smoke concentrations towards the central city, and also to the outer suburbs and rural areas beyond. The airport site recorded the lowest of the ten monitoring sites in 1976. Plate 3.1 shows the spatial extent of air pollution over Christchurch on 14 June 1976. The average daily smoke reading on this day was $176 \mu g/m^3$ at the urban site (centre, right of photograph), and $20 \mu g/m^3$ at the rural site (extreme top left). The fact that the dome of pollution appears to reach well into rural areas is a result of the height of the dome, despite the altitude at which the photograph was taken (300 metres).

Figure 3.3 Average Daily Variation in Smoke Concentration, Urban Site, June 1976.

Figure 3.4 Vertical Air Temperature and Mixing Depths, 25 June 1976.



SMOKE. (μg/m3)
300
250
200
150
100
50
0
02 04 06 08 10 12 14 16 18 20 22 00
TIME. (T.S.T.)



ALTITUDE (m)
1600
1400
1200
1000
800
600
400
200
0
450m (Urban M.D.)
325m (Rural M.D.)
2 4 6 8 10 12 14
TEMPERATURE (°C)

Plate 3.1 Christchurch City under Smog, 14 June 1976.

Source: Christchurch Press

METEOROLOGICAL FACTORS INFLUENCING POLLUTION OCCURRENCE

Dynamics of Atmospheric Dispersion

As mentioned in the previous section, all phases of the pollution process are weather dependent. The dispersion of emissions is affected by meteorological factors as is often the origin of emissions (due to physiological stress at adverse climatic conditions). The most important factor lies in the ability of the atmosphere to disperse pollutants, it's ability varying by a factor of 100,000 between extreme cases (Scorer, 1958).

Irregular random eddies occur at the surface boundary layer when air flows over obstacles, and these result in transport and diffusion of atmospheric pollutants horizontally and vertically at rates far higher than normal molecular diffusion. The degree of turbulence and the eddy size distribution from point emission sources, depend on the nature of the surface, wind speed, vertical wind profile and, most importantly, the vertical temperature profile. These last three factors are themselves affected by turbulence; therefore there is a degree of feedback.

As the vertical temperature profile is an important factor in determining the static stability of air, this will be examined in more detail. To obtain static stability in dry air, the requirement is that temperatures of the atmosphere decrease with height at less than about 9.8^{o}C/km (the temperature change caused by expansion or contraction of a gas without exchange of heat with its environment). If the lapse rate exceeds this value, the air becomes unstable to small vertical displacements and a displaced volume of air will accelerate in the direction of the original impulse. Often a layer is present in which temperatures increase with height and these are termed inversions. They are common at all levels, especially so in the surface boundary layer, and result from ground cooling at a faster rate than air overnight, with this in turn cooling surface layers of air. With cool air at the surface and warmer air above, conditions become very stable and there is strong resistance to vertical motion. High stabilities inhibit the vertical components of surface eddies and turbulence is reduced. Vertical exchange of horizontal momentum is also reduced, with the wind profile becoming steep, and light surface winds. The process involves feedback, where light surface winds retarded by surface drag facilitate further cooling, which strengthens the inversion further reducing turbulence (Scorer, 1958). This situation will continue until atmospheric characteristics are altered, either by the sun warming surfaces and the surface air, or by a synoptic weather change.

Techniques for predicting turbulence and diffusion are developing rapidly, but no method exists for obtaining quantitative results over a wide variety of conditions. One simple estimate for dispersion used in this study is that of mean mixing depth, a measure of air pollution potential based on thermal turbulence. The calculation method is outlined in a paper by Holzworth (1973). The mixing depth of the atmosphere is not obtained directly, but can be estimated from routine Meteorological Service observations. The Christchurch Airport radiosonde data from midday soundings were used to provide a vertical temperature profile. Figure 3.4 shows such a profile for 25 June 1976, a day of temperature lapse profile.

To obtain the maximum mixing depth (best conditions for dispersal) for that day, the maximum daily surface temperature is used as a base point from which a dry adiabatic lapse line (9.8^{o}C/km) is extended. The altitude at which the dry adiabatic lapse rate crosses the observed temperature profile is defined as the mixing depth. Above this point a rising parcel of air will become cooler than the surrounding atmosphere, and will tend to sink. Figure 3.4 shows a mixing depth of 450 metres and 325 metres respectively for urban and rural sites of of this study. The difference in mixing depth results entirely from the difference in maximum daily temperatures, 12°C at the urban site as against 11°C at the rural site. It can be appreciated that under strong inversion or lapse conditions the mixing depth would be quite different than for the example. The influence of a low mixing depth associated with a temperature inversion on pollution can be seen in Plate 3.2, taken in mid-winter from Ilam University towards the centre of the city. Note particularly the cut off point for pollutants near to the top of this photograph.

There are several problems with this estimate of atmospheric dispersal; the assumption that the vertical temperature profile obtained is the same as when the maximum daily temperature occurs, and the assumption that the vertical temperature profile is the same over the city as that measured at the airport. However Ryan (pers. comm.) of the Meteorological Service believes that the urban/rural profiles for this time of the day would not be too dissimilar. Another problem is that the single radiosonde record for the day does not allow hourly mixing depths to be calculated, and the maximum daily mixing depth and hourly mixing depths are likely to be of a considerably different magnitude. Despite the shortcomings of this pollution potential estimate, it remains a valuable measure in the context of this study.

<u>Urban/Rural Mixing Depths over the 1976 Study</u>

The monthly mean daily maximum mixing depths were obtained by using the above method on daily data. Table 3.9 shows the monthly average mixing depths for 1976 over the study period. The most important feature is the decreasing mixing depth towards winter, this being due to the larger number of surface based inversions with colder, calm, conditions. The other feature is the difference in monthly mean mixing depths for all months at the two sites. As the same upper air profile is used, the difference is related to the warmer maximum daily temperature at the urban site. Daily differences are statistically

Plate 3.2 View East from University of Canterbury.

(Note distinct top of pollution layer)

TABLE 3.9

Monthly Average Mixing Depths, 1976

	February	March	April	May	June
City M/D (m)	1385	939	659	688	759
Airport (m)	1150	804	601	601	516
Number of observations	6	31	27	30	25
t value	2.81	2.086	1.516	2.786	3.032
Significance (%)	5	5	20	.1	1

significant, as the t test for differences in paired variates shows. As would be expected, the significance is greatest for the winter months when temperature differences between sites are greatest. April differences are less significant, probably because of it being a cloudy month which tended to inhibit the heat island effect.

The maximum daily mixing depth recorded over the term was 2570 metres at the urban site on 23 March, a day of strong lapse conditions with surface temperatures near 30°C. The lowest maximum daily mixing depth was 100 metres at the airport on 4 July, a day with a severe surface based temperature inversion. It was no coincidence that this day had the highest daily average smoke reading of 405 $\mu g/m^3$, recorded at the urban site.

As would be expected with a method designed to estimate pollution potential, there is a fairly strong correlation between mean daily maximum mixing depths and measured air pollution. The use of the urban mixing depth and daily pollution concentrations over 100 observations gave a correlation significant at the 0.002 level, and the regression line explained 22% of the variance.

The mixing depths described above all refer to data gathered in daytime conditions. While there may be less difference in upper air characteristics between city and rural areas during the day (Munn and Stewart, 1968; De Marrais, 1961), this does not appear to be the case at night. Much has been written about the effect of the urban heat island in reducing atmospheric stability. It has been suggested that as a result of atmospheric instability there is a greater vertical mixing and fewer inversions of less intensity than in a rural area (Peterson, 1973).

A. Ryan of the New Zealand Meteorological Service carried out kytoon studies of the variation of the surface based inversions across Christchurch in the winter of 1970. The results are unpublished. The sites used were Centennial Park (near the base of the Port Hills), Hagley Park, Casebrook School (Papanui), Bromley Park, Queen Elizabeth II Park and Cuthbert's Green (Aranui).

Various statistics from the 35 soundings of June/July 1970 have been obtained (Tables 3.10(a) - (c)). Table 3.10(c) while showing a relatively high inversion height for Queen Elizabeth II Park (nearest to rural site), does not give any indication of the percentage occurrence of the inversion. The predominance of lapse conditions in urban areas and inversion conditions in rural areas out of 32 observations, is illustrated in Table 3.10(d). Table 3.10(e) shows that the strength of the inversion is far greater at the semi-rural Queen Elizabeth II Park than for any other site. Hagley Park in the central city, despite its cold surface temperatures, shows the smallest inversion intensity. Centennial Park shows the effect of cold air drainage off the nearby hills in both Tables 3.10(c) and (e).

Wind Speed and Direction

One further important factor influencing pollution occurrence involves wind characteristics. Table 3.11 shows the percentage frequency of hourly wind directions by month for each month of the study period. It can be seen that over the study period the predominant northeast and east winds of the summer were replaced by a larger proportion of southwest and west winds. Most important in terms of this study are the greater porportion of calms over the winter months. The tendency towards increasing calms is further shown in the monthly average daily wind speed for the 1976 study period (Table 3.12) which nearly halved, from 9.4 kts to 5.5 kts, between February and June. A diurnal variation in wind speed is also noticeable, with nightime winds and early morning winds being light and afternoon and evening winds being stronger due to solar heating causing turbulence. Most noticeable is the suppression of wind speed in the mornings in June, this probably being due to very stable conditions caused by deep surface based wintertime inversions. Only after these inversions are destroyed by solar heating

TABLE 3.10

Inversion Characteristics over Christchurch City

(a)

Percentage Height of Inversion (feet)

11	100 - 200
32	201 - 300
23	301 - 350
34	351

(b)

Percentage Intensity of inversion (^{o}C)

6	0 - 2
33	2.1 - 4.0
16	4.1 - 6.0
29	6.1 - 8.0
16	8.1

(c)

Average height of inversion by Site (feet)

Centennial Park	-	289
Casebrook	-	318
Hagley Park	-	331
Bromley Park	-	338
Queen Elizabeth II Park	-	356

(d)

Nature of Lower Atmospheric Temperatures

	Inversion	Neutral	Lapse
Hagley Park	7	8	18
Queen Elizabeth II Park	30	0	2

(e)

Average Intensity of Inversion by Site (^{o}C)

Hagley Park	-	4.08
Centennial Park	-	5.85
Casebrook	-	4.98
Queen Elizabeth II Park	-	10

TABLE 3.11

Average Hourly Wind Directions by Month

	N (%)	NE (%)	E (%)	SE (%)	S (%)	SW (%)	W (%)	NW (%)	Calm (%)
February	1.4	37.5	10.6	1.8	17.6	12.5	1.8	4.6	11.6
March	3.3	43.1	16.5	0.9	10.6	11.1	2.9	4,6	6.7
April	6.9	35.0	8.3	0.3	9.4	13.0	4.6	2.9	19.4
May	6.0	21.9	7.4	1.1	5.2	18.8	14.0	7.3	18.3
June	5.5	20.8	2.8	0.4	4.1	27.2	14.3	7.2	17.4

TABLE 3.12

(a) Average Hourly Wind Speed by Month (kts)

Hr	February	March	April	May	June
00	9.25	7.7	7.3	7.5	6.0
01	9.9	8.2	7.1	5.2	7.3
02	8.5	7.4	7.5	4.4	7.8
03	6.4	6.6	6.6	4.4	7.2
04	5.8	6.6	5.7	5.4	6.6
05	4.4	6.8	6.4	4.4	5.6
06	4.4	6.4	5.1	4.2	6.1
07	4.5	8.2	4.6	3.8	4.0
08	4.8	8.1	3.7	4.2	4.9
09	7.6	9.8	5.7	3.8	4.5
10	8.1	10.7	6.8	4.4	3.1
11	10.6	9.8	8.1	4.8	3.8
12	11.4	10.8	9.8	7.0	2.9
13	12.0	11.7	9.6	11.1	4.6
14	12.0	11.8	10.4	11.6	5.7
15	11.4	11.0	11.1	9.5	7.4
16	13.2	10.8	10.2	11.7	6.6
17	14.5	13.4	10.5	10.1	6.1
18	14.9	11.4	9.2	8.4	6.5
19	13.0	11.1	7.8	8.3	6.0
20	11.6	8.8	7.2	6.8	5.4
21	9.5	8.0	7.9	6.4	4.7
22	8.6	7.6	6.7	8.2	5.2
23	8.6	7.7	6.8	6.4	3.4
$\bar{X}$	9.4	9.1	7.5	7.3	5.5

(b) Average Daily Wind Speed at Airport and Central City Location (kts)

	1961	1962	1963	1964
Christchurch Airport	5.5	6.5	7.6	7.0
Cathedral Square	2.9	3.0	3.3	3.2

Source: 1966 Regional Planning Authority Report.

are wind speed increased. As described before, the situation is self-reinforcing with lower wind speeds promoting inversions, which in turn tend to suppress wind speeds. These low early morning wind speeds associated with inversions have important implications for the dispersion of pollutants within the urban atmosphere, and hence attenuation of SW$\downarrow$.

The discussion so far relates only to wind speed at the airport, and in the absence of measurements at the urban site little can be said. However, over a period of four years from 1961 wind speeds were taken by the Meteorological Service at a site in Cathedral Square for the six month winter half year (Table 3. 13). Over that period wind speeds in the city centre were nearly exactly half those at the airport, and it seems reasonable that a relationship in the same order of magnitude holds for 1976.

A relationship would be expected to exist between wind speed and pollution levels, as winds greatly help dispersion by preventing the development of inversions and promoting turbulence. England Street June hourly smoke amounts were regressed against airport wind speed, and a moderately strong negative relationship was suggested with $r = -0.44063$ (Sig. at .001), explaining 20% of the variance. This relationship presumably would be stronger if wind speed data from the England Street site was used.

The calm clear nights of winter are of special interest in this study; therefore it is of use to discuss some of the Christchurch urban wind drift patterns on nights of high pollution potential. Despite the description "calm" applied to many hourly observations, there is usually an intricate movement of air flows determined by topography and urbanisation which can only usually be measured by smoke tracing. Ryan (1975) undertook an investigation of low level airflow patterns in Christchurch on nights of high pollution potential using a dense network of observers. It was found that flow patterns on almost all occasions belong to one of three types; a northeast, southwest or northwest flow. The northwest flow is a downslope katabatic wind resulting from subsiding air off the Canterbury Plains, and often evolves later in the night from the other two flow patterns. Usually this wind is of surface origin, and unless the other winds are particularly weak, the northwest wind does not usually penetrate far into the urban area. This is ascribed by Ryan to vertical mixing, associated with greater surface roughness and the urban heat island operating to destroy the shallow layer of light northwest flow. There is also evidence of katabatic flow off the Port Hills to the south of the city. However, the influence of this flow appeared to be minimal.

Urban climatologists have surmised for some time that if a city is warmer than its surroundings, a low pressure system will be set up drawing cooler rural air along the surface, much in the same way as a pressure system in the macroscale. Ryan states that because flow patterns appear to be strongly influenced by topography in Christchurch, little evidence for a heat island circulation can be deduced. It appears that apart from the katabatic flows, the surface wind flow patterns over Christchurch on calm nights are determined by the large scale weather situation, operating in conjunction with Christchurch's position relative to Banks Peninsula.

METEOROLOGICAL FACTORS POTENTIALLY INFLUENCING SW$\downarrow$ AND LW$\downarrow$ DIRECTLY.

Urban/Rural Temperatures

The heat island effect has been studied previously in Christchurch by Sham (1968) and Kingham (1969). Both of these workers found considerable urban/rural differences in temperatures. Sham found a maximum heat island intensity of up to 6.3°C, but the intensity of the urban/rural differences was found to be determined by meteorological factors such as wind speed and cloudiness. Kingham, in a limited number of transects by motor vehicle, found urban/rural differences ranging from 2.2°C to 5.6°C. The discussion here of 1976 urban/rural temperature differences refers only to the static sites, and averages temperature over all weather conditions. The discussion of spatial patterns of radiation in Chapter 6 is supplemented by temperatures taken on traverses, and these may be more comparable with data of Sham and Kingham. Comparison with overseas data is also included in this chapter.

While it is true that the thermohydrograph and Stevenson's screen at the urban site is not located for true representativeness with the rural site, indications are that the readings outlined in Table 3.13 for all weather conditions are reasonable, if not in absolute terms, then in trends. This indicates the effects of a "heat island" which gives significant differences in hourly average temperatures for each month except April, using the t-test

$$\mu_{\text{urban}} = \mu_{\text{rural}},$$

where the observations are paired variates.

The average temperature over the whole study period was 11.32°C at the rural site and 11.89 at the urban site, a difference of almost 0.6°C. This is similar to the average 1.0°C quoted by Geiger (1973) for a number of northern hemisphere cities. The maximum temperature recorded over the term was 32°C at the city site on 22 March and the minimum recorded over the term was -5°C at the rural site on 4 July. The lower urban excess temperature in April is probably related to the cloudy nature of that month.

Averaged data for the term shows the diurnal pattern of temperature well. There is a maximum urban temperature excess in the early hours of the morning before dawn, and the excess is least in the middle of the day. In fact there is often a rural excess at this time in the warmer months, and in the cooler months under clear skies (not shown in this

TABLE 3.13

Hourly Site Temperatures by Month ($0^{o}C$)

Hr	February[x]		March		April		May		June		Term	
	Apt	City	Apt	City	Apt	City	Apt	City	Apt	City	Apt	City
01	11.3	11.2	13.1	13.8	10.2	9.7	6.8	8.0	5.1	6.4	9.3	9.8
02	10.7	11.2	12.6	13.0	9.6	9.6	6.7	7.5	4.8	6.2	8.9	9.5
03	9.3	10.9	12.2	12.8	9.6	9.4	6.4	7.3	4.4	5.8	8.4	9.2
04	9.3	10.8	11.8	12.6	8.4	9.4	5.7	6.8	3.6	5.5	7.8	9.0
05	9.0	10.5	12.1	12.4	8.8	9.2	6.0	6.4	4.0	5.2	8.0	8.8
06	9.3	10.7	12.4	12.4	9.2	8.9	6.3	6.5	3.7	5.0	8.2	8.7
07	10.3	13.2	13.4	12.9	9.25	9.5	6.4	7.5	3.4	4.6	8.5	9.3
08	13.2	15.9	14.7	14.4	10.4	10.7	6.6	9.3	3.2	4.5	9.6	10.6
09	16.2	17.9	16.4	16.1	13.1	12.7	9.4	10.8	6.0	5.6	12.2	12.3
10	17.3	19.9	17.6	17.7	14.3	14.0	11.1	12.0	7.8	7.4	13.6	14.0
11	18.8	20.4	18.4	19.0	15.1	14.8	12.4	13.0	9.3	9.1	14.8	15.1
12	19.2	20.4	18.7	19.6	15.6	15.3	12.9	13.5	10.3	10.7	15.3	15.8
13	19.7	21.4	18.8	19.5	15.7	15.5	13.2	13.8	10.7	11.2	15.6	16.2
14	20.0	21.0	18.6	19.0	15.7	15.6	13.2	13.1	10.5	11.6	15.6	16.2
15	19.2	20.1	17.9	18.1	15.0	15.0	12.7	12.2	9.9	11.24	14.9	15.5
16	18.3	18.7	16.9	17.4	13.9	14.4	11.5	11.1	8.9	10.2	13.9	14.6
17	17.0	17.0	16.3	16.4	13.2	13.6	10.5	10.3	8.0	9.0	13.0	13.4
18	16.0	16.0	15.2	15.5	12.3	13.0	9.9	9.8	7.3	8.2	12.1	12.6
19	15.0	15.4	14.7	14.9	12.0	12.2	9.5	9.2	6.7	7.7	11.6	12.0
20	14.5	14.2	14.4	14.6	11.6	11.7	8.9	9.2	6.1	7.3	11.1	11.4
21	12.3	13.2	14.1	14.2	11.1	11.4	8.5	8.7	5.9	7.0	10.4	10.9
22	12.0	12.7	13.4	13.8	10.0	10.9	7.8	8.9	4.8	6.8	9.6	10.6
23	12.0	12.4	13.1	13.5	9.8	10.6	7.8	8.7	4.8	6.4	9.5	10.3
00	12.0	12.0	13.5	13.2	10.6	10.1	7.8	8.5	4.7	6.2	9.7	9.7
$\bar{X}$	14.24	15.29	15.01	15.28	11.85	11.96	9.083	9.581	6.41	7.46	11.32	11.89
T =	5.699		3.597		1.276		5.334		8.003		10.143	
Sig. =	0.001		0.002		N.S.		0.001		0.001		0.001	

[x] Limited sample.

table). These findings are similar to those of Mitchell (1962). The reason for the trend is the differing thermal capacities of nearby surfaces at each site, temperatures tending to heat up and cool down at the rural site more quickly than at the urban site.

Parallelling the diurnal trend is a seasonal trend towards maximum urban excess temperatures in the colder months. Because of the few number of days (5), February is a poor sample and does not follow this trend. It should not be forgotten that the temperatures observed at airports are higher than those of true natural environments (Ludwig and Kealoha, 1968, in McBoyle, 1973). Therefore true urban/rural differences are likely to be greater than discussed here.

The consistent urban excess warmth is a likely influence on incoming long wave radiation, this even more so considering that the excess may exist up to an altitude of 300 metres (Bornstein, 1968). It is this lower layer of the atmosphere that also contains the greatest quantities of water vapour and dust. Therefore the greater urban warmth acting through these other media can increase the LW↓ potential emittance of the atmosphere.

Vapour Pressure

As with temperature there is a divergence in vapour pressure (actual water vapour present in the atmosphere corrected for temperature and air pressure) between the central city site and the airport site, amounting to 2.5% over the term and considerably more for individual months (Table 3.14). The 0.2 mb difference over the term is identical with the annual difference observed by Chandler (1965) in London and at a nearby rural location. Chandler (1967) also frequently observed that at night the urban vapour pressure was higher than in outlying regions, especially when meteorological conditions were conducive to the formation of a heat island. The June data shows this well (June being conducive to heat island formation), with the city having an average excess vapour pressure from about 2100 hrs until 0400 hrs or later of about 0.5 mb. Individual hourly deviations at this time amounted to up to 2 mb.

TABLE 3.14

Hourly Vapour Pressure by Month (mb)

Hr	February[x]		March		April		May		June		Term	
	Apt	City	Apt	City	Apt	City	Apt	City	Apt	City	Apt	City
01	13.5	14.3	11.7	11.7	8.7	8.3	7.9	7.7	5.1	5.5	8.3	8.3
02	12.5	13.7	11.4	11.8	8.5	7.4	7.9	7.6	5.1	5.3	8.2	8.0
03	12.3	11.6	11.6	11.8	8.2	7.2	7.8	7.5	4.9	5.0	8.1	7.8
04	12.3	11.2	11.1	11.5	7.3	7.3	7.5	7.2	4.7	5.3	7.8	7.7
05	12.3	11.7	11.7	11.2	7.4	7.4	7.2	7.2	4.9	4.8	7.6	7.5
06	12.1	11.8	10.9	11.4	7.3	7.1	7.3	6.9	4.8	4.7	7.6	7.5
07	14.9	12.9	12.1	11.6	7.2	7.1	7.0	6.7	4.6	4.5	7.7	7.5
08	15.7	13.1	13.2	12.2	9.2	8.2	7.8	7.3	4.6	4.6	8.7	8.0
09	13.1	13.3	12.6	12.5	10.0	9.2	8.1	7.8	5.6	4.6	9.1	8.5
10	11.5	11.4	12.6	13.0	10.0	7.0	7.8	7.7	5.9	4.7	9.1	8.1
11	12.2	11.7	11.9	12.7	10.0	9.4	8.5	7.8	6.0	5.0	9.1	8.7
12	12.7	12.2	11.7	12.6	10.1	9.3	8.3	7.9	6.4	5.8	9.1	8.9
13	13.1	14.4	10.9	11.8	10.3	9.9	8.7	8.3	5.6	6.0	8.7	9.0
14	14.6	8.75	10.8	12.0	10.1	10.7	8.5	8.4	5.7	6.2	8.8	9.3
15	9.6	8.6	11.3	11.0	11.1	10.5	8.9	8.9	6.9	6.5	9.5	9.2
16	11.0	9.8	12.7	12.1	10.7	10.6	9.2	9.3	6.9	6.5	9.9	9.6
17	11.7	10.7	12.5	12.2	11.1	10.7	8.9	8.9	7.3	6.3	10.0	9.5
18	11.6	11.6	13.0	12.6	11.1	10.8	9.1	9.2	6.7	6.3	10.0	9.7
19	12.0	11.8	12.9	12.4	11.2	11.0	9.1	9.2	6.7	6.1	10.0	9.7
20	13.6	12.3	12.7	12.6	11.2	10.6	9.2	9.2	6.4	6.1	9.9	9.7
21	13.4	12.3	12.6	12.4	11.1	10.7	8.9	8.9	6.1	6.3	9.7	9.6
22	13.2	13.2	12.3	12.1	10.9	10.7	8.7	9.0	5.4	5.9	9.3	9.5
23	12.3	12.6	12.0	11.9	10.8	10.9	8.5	8.8	5.0	5.6	9.1	9.3
00	11.9	12.6	12.1	11.9	10.7	10.2	8.9	8.7	4.8	5.2	9.1	9.1
$\bar{X}$	12.0	12.7	12.00	12.00	9.8	9.2	8.3	8.1	5.7	5.5	8.9	8.7

[x] Limited sample

Chandler attributed the higher urban nocturnal vapour pressures to a lower rate of diffusion of air near ground level between tall city buildings during nights of light winds. This air with its high daytime moisture was trapped in the city canyons and remained there into the evening keeping the absolute humidities high. Another possible explanation is the lack of cool surfaces for dew formation in the city as compared to rural areas, with moisture having to remain in the atmosphere.

However, on the average, the urban absolute humidities (vapour pressure) are slightly lower due to the fact that evaporation rates in the city are lower because of markedly different surface materials. Rural surfaces tend to retain moisture while city surfaces promote quick run off.

The very small differences in urban/rural vapour pressure make it unlikely to be an important influence on either SW$\downarrow$ or LW$\downarrow$ variation between the sites. However, this is discussed in later chapters.

CONCLUSIONS

The most important points arising from this study of the variation of some non-radiation parameters across Christchurch may be summarised as follows:

1) Smoke values averaged over the study period show a considerable excess at the central city site over the airport site, reaching a maximum average concentration of 106 $\mu g/m^3$ (20 $\mu g/m^3$ at airport) in June and July. The summer months show little difference in smoke pollution.

2) There is an observable daily trend in smoke pollution with one peak at 0900 hrs and another around 1900 hrs.

3) Estimations of maximum daily mixing depths indicate a seasonal trend toward increasing atmospheric stability in the winter months and also indicate a tendency for urban mixing depths to be higher with inversions less frequent and weaker.

4) Observed wind speeds at the airport tend to decrease towards winter and there is evidence that winds at the central site are up to half those at the rural site. Northeast and east winds of summer were replaced by a greater proportion of west and southwest winds and calms in the winter months. There is evidence that wind drift under calm conditions is influenced by topography, rather than by urban effects.

5) Temperature differences, with an urban excess, were found to occur throughout the term of study, with the maximum excess occurring in the very early morning.

6) A divergence in absolute humidity (vapour pressure) was also found to exist, with airport values generally being higher than urban values. However under suitable conditions an urban excess was occasionally observed.

CHAPTER FOUR

URBAN/RURAL SHORT WAVE RADIATION CHARACTERISTICS

INTRODUCTION

The two primary concerns in this chapter are to discuss urban/rural variations in short wave radiation, and to outline possible causes for these variations. Where possible, comparisons with studies in other cities are made as this may give some idea of the effect of degree of urbanization on SW$\downarrow$.

This analysis relies almost solely on the consideration of summary parameters. However raw data on which this thesis is based will be bound separately and will be lodged in the Map Library, Geography Department, University of Canterbury. The volume will be entitled "Raw data from investigations of urban/rural radiation differences across Christchurch."

AN EXAMINATION OF SHORT WAVE RADIATION CHARACTERISTICS OF CHRISTCHURCH

Urban/Rural Differences in Total SW$\downarrow$

A statistical analysis of the total record was undertaken on the hourly values of total SW$\downarrow$ by division of the data into clear days, partly cloudy days and overcast days. The relative distribution of these types within the total record is outlined in Table 4.1. Partly cloudy days (3/8 - 6/8 cloud) made up 56% of the total record, clear days ($\leqslant$ 2/8) were 28% of the total and overcast days ($\geqslant$ 7/8) were 16%. Fortunately there was a high percentage of clear days during this study, mainly because of the extremely clear anticyclonic weather of early and late June.

A two tailed t-test on hourly urban and rural total SW$\downarrow$ values was performed on a standard 100 pair sample, testing the hypothesis,

$$\mu_{Rural} = \mu_{Urban} ;$$

where the rural and urban values are paired variates.

TABLE 4.1

Hourly SW↓ Urban/Rural Differences

	Clear		Partly Cloudy		Overcast		Total	
No. Days	33		65		18		116	
	U	R	U	R	U	R	U	R
$\overline{X}$ Hrly SW	301.3	326.15	202.5	208.2	122.3	124.3	218.16	228.72
t-test (100 obs.)	9.587		0.3123		0.29802			
Signif.	0.0001		N.S.		N.S.			

It was found that clear weather urban/rural SW$\downarrow$ differences were significant at the 0.001 level, with the other data being not significant (Table 4.1). Thus all subsequent analysis is of urban/rural SW$\downarrow$ differences is restricted to clear days. This also makes the analysis more comparable with the short term variety of previous studies (Table 1.3). The reason for the partly cloudy and overcast days showing no significant urban/rural differences can partly be explained by the problems of interpreting radiation charts for these days, when there is a considerable amount of error induced by the fluctuating nature of the trace. Of more importance is the physical effect of cloud, cutting the proportion of time that the solar beam passes directly through the atmosphere, therefore limiting the time that atmospheric particulates alone have an effect on the solar beam.

As the study period extended from late summer through to mid-winter the variation in SW$\downarrow$ was seasonally marked. Table 4.2 shows a sample of 20 clear days from throughout the study period chosen for an almost complete lack of cloud, the expected average daily radiation outside the atmosphere, the received radiation at each of the two sites, and the percentage difference between sites by day and by month. The average SW$\downarrow$ urban/rural difference for the 20 clear days was 14.9% with differences ranging between -1.1% and 30% for individual days. These values are comparable with those recorded in many large overseas cities (Table 1.3),but it should be remembered that this sample does not cover the whole year and concentrates on the most polluted part of the year.

The trends in percentage difference are clearly seasonal in character as is shown in Table 4.2 and Figure 4.1. Lowest daily differences occur in late summer and autumn while the highest differences occur in winter. When average monthly daily radiation for the clear days is plotted for both sites (Figure 4.1) it can be noted that the absolute energy difference between the two sites remains fairly constant, while the percentage difference becomes greater with the lower absolute values

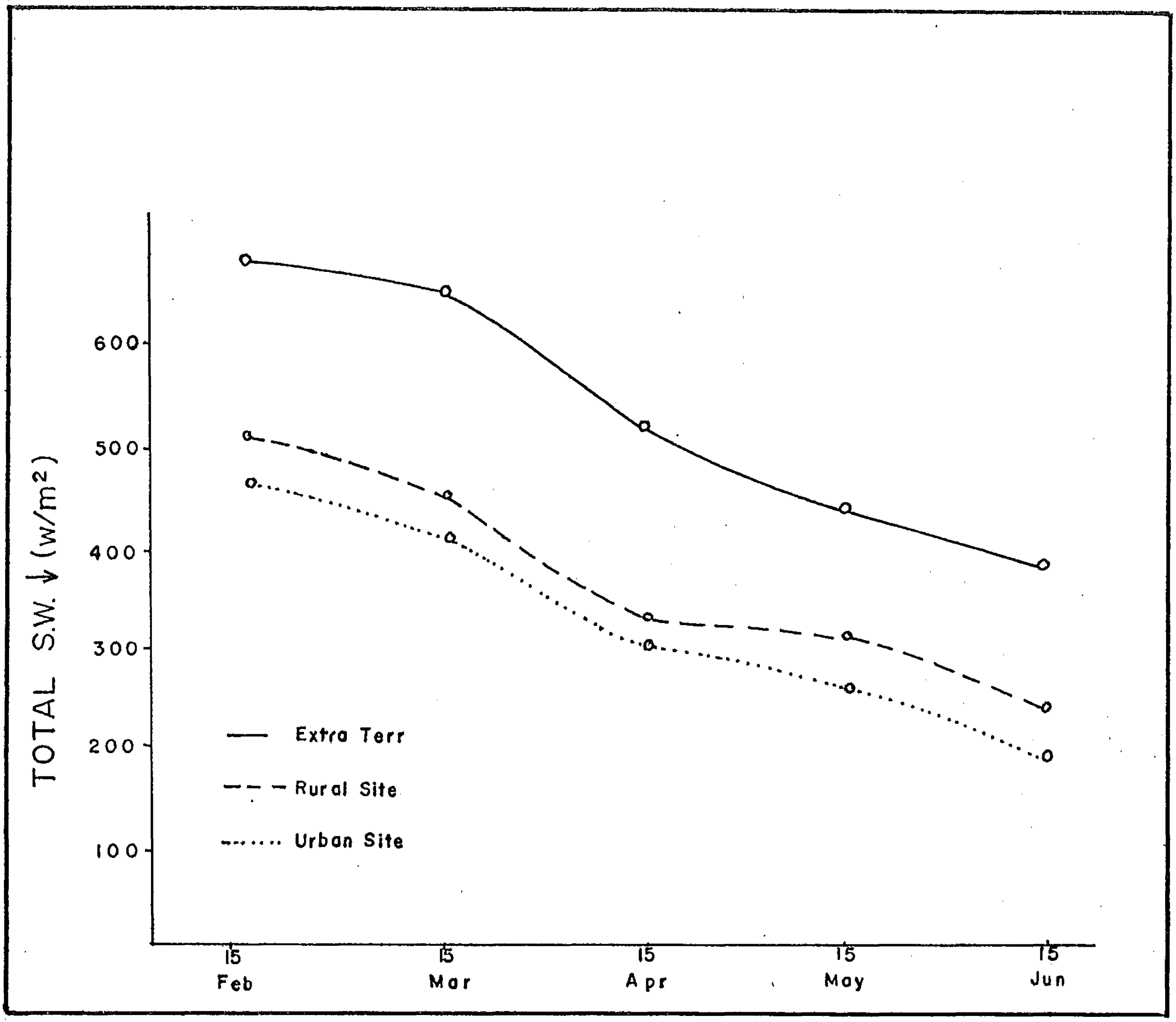
TABLE 4.2

Daily Average SW↓ by Site (w/m^2)

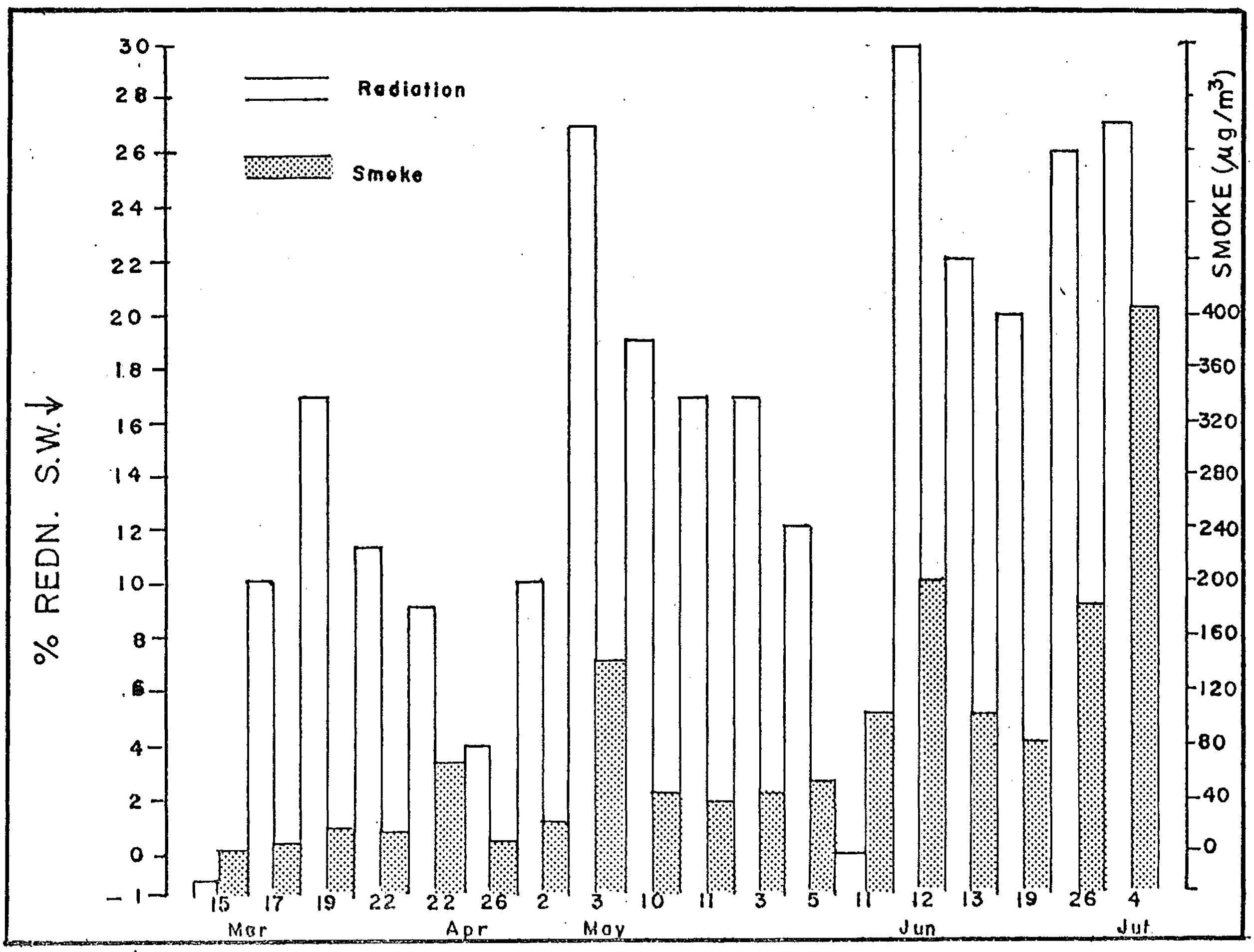
Date		Expected	City	Airport	U/R % Diff.[1]	% Diff. by Month	t-test
February	24	680	463	508	9.5	11.0	t = 10.070 D. of F. = 29 Signif. = .001
	25	680	446	502	2.5		
March	15	660	450	446	-1.1	9.25	t = 8.162 D. of F. = 78 Signif. = .001
	17	660	405	448	10.6		
	19	650	396	461	16.4		
	22	670	387	430	11.1		
April	22	520	294	321	9.1	6.6	t = -1.302 D. of F. = 78 Signif. = .001
	26	500	313	326	6.6		
May	2	460	290	316	9.6	18.1	t = 14.352 D. of F. = 68 Signif. = .001
	3	460	261	331	26.8		
	10	450	247	294	19.0		
	11	450	247	287	17.0		
June	3	400	190	223	17.3	19.27	t = 16.842 D. of F. = 92 Signif. = .001
	5	390	185	208	12.4		
	11	380	220	220	0.0		
	12	370	186	247	30.0		
	13	370	189	230	21.6		
	19	330	210	252	20.0		
	26	370	189	238	25.9		
July	4	380	185	235	27.0		

Figure 4.1 Monthly Averages of Daily Urban and Rural SW Radiation

Figure 4.2 Comparison of Urban/Rural Radiation and Recorded Urban Smoke



TOTAL S.W. ↓ (w/m²)
600
500
400
300
200
100
Extra Terr
Rural Site
Urban Site
15 Feb
15 Mar
15 Apr
15 May
15 Jun



% REDN. S.W.↓
SMOKE (μg/m³)
Radiation
Smoke
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-1
400
360
320
280
240
200
160
120
80
40
0
15
17
19
22
22
26
2
3
10
11
3
5
11
12
13
19
26
4
Mar
Apr
May
Jun
Jul

of SW$\downarrow$ during the winter period. A similar trend can be recognised with respect to the total possible radiation.

The main reason for this seasonal trend is probably solar path length. As shown in Table 4. 3, the SW$\downarrow$ expressed as a percentage of possible, decreased for both urban and rural sites with decreased solar altitudes. However, there is a greater decrease in this measure at the urban site as indicated by the urban/rural percentage difference, and this probably relates to the effect of particulate matter which has been shown to have a distinctly seasonal trend. The lower values for March and April may relate to increased windiness with a consequent dispersal of pollutants.

As well as solar altitude, smoke is an important additional factor which helps to explain the urban/rural differences. An initial comparison of SW$\downarrow$ urban/rural % with recorded urban smoke (Figure 4. 2), indicates a strong relationship which will be discussed in detail presently. The relationship appears to be good except in the early part of the study when other attenuating agents appear to be operating. In the winter, on occasions where the trend does not follow as well (11/6), this may be explained by the bulk of smoke being recorded during the night. The fact that there was a very high smoke reading on 12 June supports this observation.

The interaction of path length and pollution level also occurs at the daily time scale as shown in Table 4. 4 which illustrates daily trends for all clear winter days. Two distinct trends are discernible. There is a daily trend in line with solar altitude, the amount of dirty atmosphere the solar beam passing through being relatively greater at the urban site as compared to the rural site, this amount varying with solar altitude. For solar altitudes of less than 5° reductions reach greater than 50%. As well as the trend due to solar altitude, there is a trend in direct connection with measured smoke amounts (urban smoke minus the average background rural smoke). There is a secondary peak

TABLE 4.3

Clear Day Total SW↓ as Percentage of Possible

	Rural	Urban	% Difference
February	74	66	12.1
March	69	62	11.3
April	63	59	6.7
May	67	57	17.5
June	62	51	21.6

TABLE 4.4

Winter Hourly Urban/Rural Percentage of Difference SW↓

Time (T.S.T.)	Solar Altitude	% Difference SW	Smoke Urban/Rural $\mu g/m^3$
7 - 8	5^o	58.0	48.0
9	13^o	25.3	86.0
10	19^o	28.0	160.7
11	22^o	23.9	122.4
11 - 12	24^o	18.8	115.3
13	24^o	17.7	48.44
14	22^o	11.8	41.0
15	19^o	6.2	14.1
16	13^o	11.0	29.8
16 - 17	5^o	53.0	45.0
		25.3	96.3

reduction of 28% between 0900 and 1000 T. S. T. associated with a peak smoke reading of 160 $\mu g/m^3$. The lowest daily reduction of 6.2% occurs in connection with the lowest daily smoke amount of 14.1 $\mu g/m^3$, despite the fact that the solar altitude is again decreasing by 1430 hours. The decreasing SW↓ urban/rural % appears to be closely related to the break up of the inversion layer over the city which allows the release of trapped pollutants.

Urban effects on total SW↓ as described appear to agree well with the literature, with attenuation being greatest at longer solar path lengths (Oke, 1974). This relationship holds both seasonally and daily. There also appears to be an "in phase" relationship with an annual and daily pollution cycle as described by others (East, 1968; Probald, 1972). The average daily attenuation over the period of 14.9% is high, even by international standards (Table 1.3), though this may relate partly to the time of year under consideration. Even so, the degree of attenuation suggested in this study has implications as regards the use of solar radiation as an energy resource in the metropolitan area, at least in the winter time.

Urban/Rural Differences in Diffuse Beam SW↓

For a given location, the proportion of diffuse in the total solar radiation depends upon the solar altitude, the solar declination, the degree of atmospheric turbidity, the amount of water vapour present and the cloudiness (Drummond, 1955). Of these factors, cloudiness is the most significant. This study removes the problem of cloud effects by considering only cloudless data, and with this restriction lifted it can be hoped to discover the reasons for any differences in diffuse beam between sites assuming the same latitude and altitude.

There are few references to urban/rural differences in diffuse beam radiation in the literature. References made suggest that in addition to gross depletion of SW↓, there is a tendency to increase the proportion arriving as diffuse beam at the urban surface (Oke, 1974). This statement was tested with the calculation of diffuse as a percentage of total SW$\downarrow$ by hour for each of the three seasons represented in this study (Table 4. 5). This indicates that the proportion of diffuse beam in the urban area is greater in autumn and winter but not in summer However, the hourly differences of 50 paired observations from the autumn and winter seasons are not significant by t-test.

In accordance with theory (Drummond, 1955) the proportion of diffuse to direct radiation becomes greater with decreasing solar altitudes. This can be noted both seasonally and daily in Table 4. 5. With solar altitudes less than 10^{o}, diffuse beam radiation generally makes up greater than 25% of total SW$\downarrow$, but with the sun at its zenith the proportion of diffuse beam is least, amounting to less than 9% for summer conditions and 13% or less for winter conditions. The tendency for diffuse to be greater at the urban site compared to the rural site in winter and not in summer appears to be related to the seasonal cycle in smoke pollution.

In order to examine smoke effects on diffuse beam radiation, the urban percentage diffuse radiation for each season at different solar elevations was tabulated (Table 4. 6). Perhaps surprisingly, this shows that for the same solar elevations the summer proportion of diffuse is greater than for the other seasons. Therefore the high diffuse amounts of winter appear to be simply related to the low solar elevations occurring over a longer portion of the day than for the summer data, and are not related to smoke amounts at any particular solar elevation. However, the proportion of diffuse at the urban and rural sites in the winter does seem to suggest some degree of relationship to smoke.

In the absence of substantiating evidence, two possible hypotheses can be made. The first hypothesis is that the greater amount of water vapour able to be held in the atmosphere in the summer is responsible for scattering within the solar beam. This statement appears reasonable

TABLE 4.5

Clear Day Diffuse Radiation as a Percentage of Total

T.S.T.	Summer (24/2 - 31/3)		Autumn (1/4 - 15/5)		Winter (16/5 - 4/7)	
	Rural	Urban	Rural	Urban	Rural	Urban
06 - 07	25.2	27.75				
08	16.8	20.53	28.76	26.46	33.2	36.14
09	16.38	14.68	18.5	19.5	20.8	21.38
10	11.5	11.1	12.83	14.83	14.74	15.67
11	10.16	9.67	11.0	11.46	13.05	14.89
12	8.96	8.46	9.61	11.47	10.94	12.61
12 - 13	8.96	8.33	10.17	11.99	10.86	12.75
14	9.76	8.33	10.82	13.66	12.68	13.41
15	12.18	10.76	13.45	15.87	16.9	16.64
16	16.3	13.26	24.42	21.78	26.12	21.15
17	23.13	17.57	35.0	36.0	36.2	36.4
17 - 18	37.1	30.29				
X	16.36	15.06	17.46	18.3	19.55	20.14
t	1.3101		1.2073		0.9352	
D. of F.	48		48		48	
Significance	.20		N.S.		N.S.	

TABLE 4.6

Urban Diffuse Radiation as a Percentage of Total

by Solar Elevation

Solar Elevation	Summer	Autumn	Winter
Less than 10^{o}	31.0	33.5	25.0
20^{o}	25.0	22.0	14.4
30^{o}	17.21	14.4	14.0
40^{o}	14.0	12.3	-
50^{o}	10.44	-	-
60^{o}	9.0	-	-

in consideration of the theory (Drummond, 1955) and with an examination of water vapour characteristics from the previous chapter. The second hypothesis has even less substantiating evidence but has potentially more significance in the terms of this study. The diffuse radiation, being higher for a given solar path length in summer, may be a result of the pollution type in summer (possibly photochemical), which is more favourable for forward scattering of radiation than that of the winter. It is known that natural atmospheric dust has the property of scattering approximately 75% of incident solar radiation forward, and 25% backwards, with the relative proportion depending on the size of the particles (Robinson, 1967). It is possible that in winter there is a lower diffuse proportion because, rather than forward scattering, the larger smoke-type particulates in the urban atmosphere cause more backscatter and absorption with a more complete loss to the total energy income. The much smaller particulates assumed present in the urban atmosphere in summer absorb much less radiation and scatter more of the incident radiation forward. This hypothesis is discussed again later in this chapter in conjunction with computer simulation analysis, but within the scope of this study the hypothesis is impossible to test.

Urban/Rural Differences in Atmospheric Transmissivity

Direct beam short wave radiation is that part of the $SW\downarrow$ which reaches the surface without any form of scattering in the atmosphere by particulates or gases. Few urban climatological studies measure diffuse beam radiation, while measurements of Q alone are also relatively rare. However it is an important measure of atmospheric opacity for the reasons mentioned above.

The disadvantage with all the radiation variables mentioned, is that they are not constant during the day and year, and are therefore not able to be compared directly with one another. It is therefore desirable to express direct beam SW$\downarrow$ as an atmospheric transmissivity coefficient (Tr) which is given by:

$$Tr = \left(\frac{Q}{S/r^2 \text{ (Sin A)}} \right)^{\frac{1}{m}} \qquad \ldots. \; (4.1)$$

where, S = the mean solar radiation constant (1360 w/m^2)

r = the radius vector (which corrects S for earth/sun distance)

A = Altitude of the sun given by latitude, solar declination and time of day

Q = measured direct beam SW

m = Optical air mass (relative amount of atmosphere that radiation has to pass through), depends on air pressure and solar altitude.

Tr was calculated using the computer programme "SUNGEN" in Appendix IV. This yields a coefficient varying between 0 and 1, which expresses the proportion of direct beam radiation that would penetrate the atmosphere with the sun at its zenith. Hence the measure is independent of the time of the year or day, and is an ideal measure for the examination of urban effects on the transmission of solar radiation.

Previous studies have indicated atmospheric transmissivities that can be expected for different atmospheric conditions. Nishizawa and Yamashita (1967) suggested that clear day atmospheric transmissivities for heavily polluted urban areas were generally < 0.65, less polluted areas < 0.75, and clear country areas > 0.80. Sanderson et al. (1973) quoted urban transmissivities for a site in Windsor, Ontario, at 0.782 averaged over nine clear days in winter. The Tr value for a rural site 10 km from the city centre (similar to the rural site in this study), was 0.853. In a later study Sanderson (1974) quotes transmissivity values from 56 cloudless days for a site in Windsor. In her sample no days had a Tr less than 0.8, 45% had values between 0.7 and 0.8, 38% between 0.6 and 0.7, and 17% of clear days had atmospheric transmissivities of less than 0.6. The average urban transmissivity was 0.65, considerably lower than the value quoted in the earlier study. The difference between Tr values in her two studies may be due to differences in computation, or may be due to differences in water vapour between winter (1973 study) and yearly data.

Unfortunately none of these papers defines the transmissivity coefficient, and it is not clear whether they include a correction for optical air mass, or merely consist of a ratio of measured direct beam radiation to that predicted for the top of the atmosphere. For example, at a solar altitude of 30°, optical air mass m = 2.4. If the ratio of radiation at the top of the atmosphere with that measured under these conditions was 0.65, this would give a value of Tr = 0.8344 in this study. For this reason comparison with these studies is on rather uncertain grounds.

Average daily transmissivities for both urban and rural sites in Christchurch have been tabulated and classified according to percentage occurrence in each grouping by season (Table 4.7). Data refers to the 33 clear days occurring during this study period. It can be seen that through all seasons the transmissivity values are greater at the rural site as compared with the urban site. The trend becomes more pronounced in the winter as might be expected with increasing pollution. Bearing in mind the reservations stated previously, this study tends to show greater atmospheric opacity than most examples stated in the literature, although the results of Sanderson et al. (1973) are reasonably comparable.

Table 4.8 is a table of average Tr values on individual days selected for lack of cloud, and shows a similar seasonal trend to Table 4.2. The presence of three days in early June which were warmer and windier than normal is responsible for the lowered urban/rural difference for that month. The average Christchurch urban transmissivity obtained from

TABLE 4.7

1976 Daily Clear Day Transmissivities by Season
(Percentage Occurrence)

(a) Summer

Tr	Urban	Rural
> 0.84	-	-
0.81 - 0.85	16	50
0.76 - 0.81	66	50
0.71 - 0.75	16	-
< 0.71	-	-

N = 11

(b) Autumn

Tr	Urban	Rural
> 0.85	-	-
0.81 - 0.85	-	66
0.76 - 0.81	83	33
0.71 - 0.75	16	-
< 0.71	-	-

N = 5

(c) Winter

Tr	Urban	Rural
> 0.85	-	87.5
0.81 - 0.85	62.5	-
0.76 - 0.81	25	12.5
0.71 - 0.75	12.5	-
< 0.71		

N = 14

(d) Term

Tr	Urban	Rural
> 0.85	-	35
0.81 - 0.85	30	40
0.76 - 0.81	55	25
0.71 - 0.75	15	-
< 0.71	-	-

N = 33

TABLE 4.8

Average Daily Transmissivity by Site

		Tr_U	Tr_R	%	% Urban/Rural by Month
February	24	.8033	.8286	2.96	
	25	.7599	.7810	2.92	2.9
March	15	.7776	.7791	0.28	
	17	.7722	.7938	2.8	
	19	.7813	.8092	3.6	
	22	.7520	.7817	3.9	2.6
April	22	.7727	.8405	8.8	
	26	.8084	.8484	4.9	6.8
May	2	.7598	.8138	7.1	
	3	.7578	.8246	8.81	
	10	.7978	.8741	9.6	
	11	.7281	.7703	5.8	7.8
June	3	.7920	.8220	3.8	
	5	.7716	.7870	2.0	
	11	.8507	.8758	2.9	
	12	.8067	.8570	6.3	
	13	.7177	.7684	7.1	
	19	.8462	.8959	5.9	
	26	.8197	.8874	8.3	
	4	.8136	.8676	6.63	5.5
X		.7844	.8253	5.22	

this table was 0.7844 and the rural 0.825. Table 4.9 compares the seasonal hourly Tr for each site. In all seasons the first and last Tr value for the day should be ignored as the optical air mass term error and cosine error of instrumentation is greatest at low solar elevations (Rouse et al., 1973). At all seasons rural Tr is higher and there also appears to be a trend towards increased Tr in the winter months. One possible reason for this is the lower water content of the atmosphere above both sites in the winter, and this is examined later in the chapter. The hourly Tr difference for each site is significant at the .001 level.

Still ignoring the first and last hourly value, the average hourly Tr for the urban site varies 11% through the day in summer as compared with 17% and 15% for the other two seasons, despite the higher absolute Tr values for the other seasons. Tr urban/rural % differences in summer are constant through the day, with a tendency to peak at around T.S.N. Both autumn and winter seasons exhibit a marked peak of over 10% urban/rural attenuation at mid to late morning, followed by a decreasing difference. The reason for these seasonal differences can be perhaps explained by the attenuating agent responsible. The mid-year differences are apparently attributable to smoke collecting under inversion conditions and dispersing about T.S.N. with the break up of the inversion. Hourly smoke data (Table 4.4) substantiates this. In the absence of measurements of summer-type pollutants, the reasons for Tr urban/rural % differences are not entirely clear. However, it is possible that the summer attenuator is a photochemical type smog which acts through most of the day with little variation.

An examination of seasonal average Tr values obtained from Table 4.8 reveals an interesting trend which supports the above hypothesis. Urban average Tr values vary little, from 0.7831 in summer through 0.7770 to 0.7990 in winter. In comparison, rural Tr values vary much more; from 0.8031 in summer through 0.8300 to 0.8540 in the winter.

TABLE 4.9

Seasonal Hourly Transmissivities of Christchurch

Urban and Rural Sites

	Summer (to 31.3.76)			Autumn (to 15.5.76)			Winter (to 4.7.76)		
	Urban	Rural	% u/r	Urban	Rural	% u/r	Urban	Rural	% u/r
5- 6	.9570	.9500	0.7	-	-	-	-	-	-
6- 7	.7994	.8343	5.5	.8520	.9306	9.1	-	-	-
7- 8	.7679	.7560	-1.5	.8399	.9260	10.2	.8800	.8900	1.1
8- 9	.7612	.8062	5.9	.7992	.8809	10.2	.8231	.8720	6.0
9-10	.7630	.7987	4.6	.7797	.8650	10.9	.7690	.8349	8.6
10-11	.7615	.8035	5.5	.7954	.8531	7.2	.7906	.8692	9.9
11-12	.7711	.8065	4.5	.7807	.8459	6.5	.7946	.8645	8.8
12-13	.7674	.8040	4.7	.7794	.8297	6.4	.7742	.8575	10.7
13-14	.7746	.8056	4.0	.7720	.8151	5.6	.8021	.8473	5.6
14-15	.7823	.8074	3.2	.7759	.8089	3.9	.8169	.8467	3.6
15-16	.7862	.8104	3.1	.7337	.7338	0.0	.8275	.8399	1.5
16-17	.8119	.7900	-2.8	.7140	.7387	3.4	.8995	.8900	-1.0
17-18	.8503	.8075	-5.3	.8069	.8500	4.0	-	-	-
18-19	.9013	.9066	0.5	-	-	-	-	-	-
t =	6.832			12.053			10.436		
D. of F. =	121			111			148		
Significance =	.001			.001			.001		

This represents a variation of 6.3% compared with 2.8% for the urban site. There can be two possible explanations for this. Either the winter effect of decreasing atmospheric water vapour is being compensated for by more pollution at the city site, or a summer-type atmospheric pollution is being replaced by a winter-type localised pollution. The presence of particulates in winter possibly also provides condensation nuclei which would boost SW$\downarrow$ attenuation. At the airport the more extensive, higher, summer pollution is not being replaced by the more localised smoke pollution; hence the winter Tr values at the airport rise considerably. Both of these mechanisms may operate but in the absence of more detailed measurements the real reason must remain conjectural.

FACTORS INVOLVED IN URBAN/RURAL VARIATIONS IN SW$\downarrow$

Up to this point attention has focused on urban/rural differences in SW$\downarrow$, Q and Tr, although broad relationships between these variations and other characteristics which vary on a similar seasonal and daily cycle have been discussed. This section attempts to establish these correlations on a firmer basis by using both simple and multiple correlation and regression analysis. Tr is used exclusively in this analysis for reasons mentioned earlier.

It should be emphasised that a good correlation between two variables does not necessarily mean a cause and effect relationship unless there are good theoretical reasons for believing this to be the case. This analysis looks at variables which, theoretically, can contribute directly (e.g. smoke) or indirectly (e.g. wind) through their effect on other variables. Finally, an attempt is made to establish the effect of mechanisms which operate directly, using a simulation model.

Smoke Pollution

As all recent studies of attenuation of SW$\downarrow$ in urban areas isolate atmospheric pollution as the most important agent of reduction (Oke, 1974), it seems that this would be the most suitable place to start in a consideration of Christchurch urban/rural Tr variations.

The application of linear regression to up to 205 observations from throughout the study period resulted in the regression coefficients shown in Table 4.10. Note that in the absence of hourly smoke readings from the rural site, smoke is expressed as the hourly value at the urban site minus the daily average at the airport. In some cases there is therefore a negative smoke reading. The regression matrix shows the relationship of urban/rural transmissivity percentage difference (Tr urban/rural %) for all data, and winter data with both smoke (S) and log smoke ($\log^S$). Ordinary transmissivity values for the urban site (Tr_U) are shown in the same way.

Two trends are clear for both Tr urban/rural % and Tr_U. There is a definite seasonal trend, with the correlation coefficient being better for winter data than for full term data. This probably shows the increasingly dominant effect that smoke pollution has in the winter. This shows up particularly well in the Tr_U against $\log^S$ relationship where the yearly data shows no significant relationship, while the winter data is significant at the 0.01 level. The trend for better correlations with $\log_{10}$ smoke results from the log normal distribution of smoke readings. A logarithmic transformation on smoke reduces the extreme values for smoke (400 $\mu g/m^3$ +) to a series of points which can fit the regression line more closely. Smoke data alone explains 47% of the variance with Tr urban/rural % in winter, while $\log^S$ explains more than 10% more of the variance.

An examination of the a coefficient on yearly Tr urban/rural % regression against smoke shows an initial 3.3% reduction in urban

TABLE 4.10

Summary of Regression Analysis (Smoke)

Dependent Variable	SMOKE (S) No. Obs.	a	b	r	Signif.	LOG SMOKE (LOG^S) No. Obs.	a	b	r	Signif.
Term Tr U/R %	205	3.2636	0.033538	0.4977	.01	205	1.4084	3.1825	0.5650	.01
Winter Tr U/R %	505	-0.0130	0.08417	0.6875	.01	50	-0.74056	4.3621	0.7581	.01
Term Tr_U	205	0.7985	-2.9280	-0.003	N.S.	205	0.7904	0.00790	0.09784	N.S.
Winter Tr_U	-	-	-	-	-	50	0.85872	-0.02669	-0.4901	.01

transmissivities with no smoke. This relatively high intercept on the Y axis suggests the presence of an attenuating agent in the summer and autumn season, an observation supported by the fact that the regression line on winter data passes more nearly through the origin. As would be expected, the relationship between percentage reduction in transmissivity and increased smoke is positive, while straight transmissivities (Tr_U) show a negative relationship. Figure 4.3 illustrates relationship between the winter Tr urban/rural % and $\log^S$. The equation of the regression line is,

$$\text{Tr urban/rural } \% = 4.3621 \log^S - 0.74056 \qquad \ldots. (4.2)$$

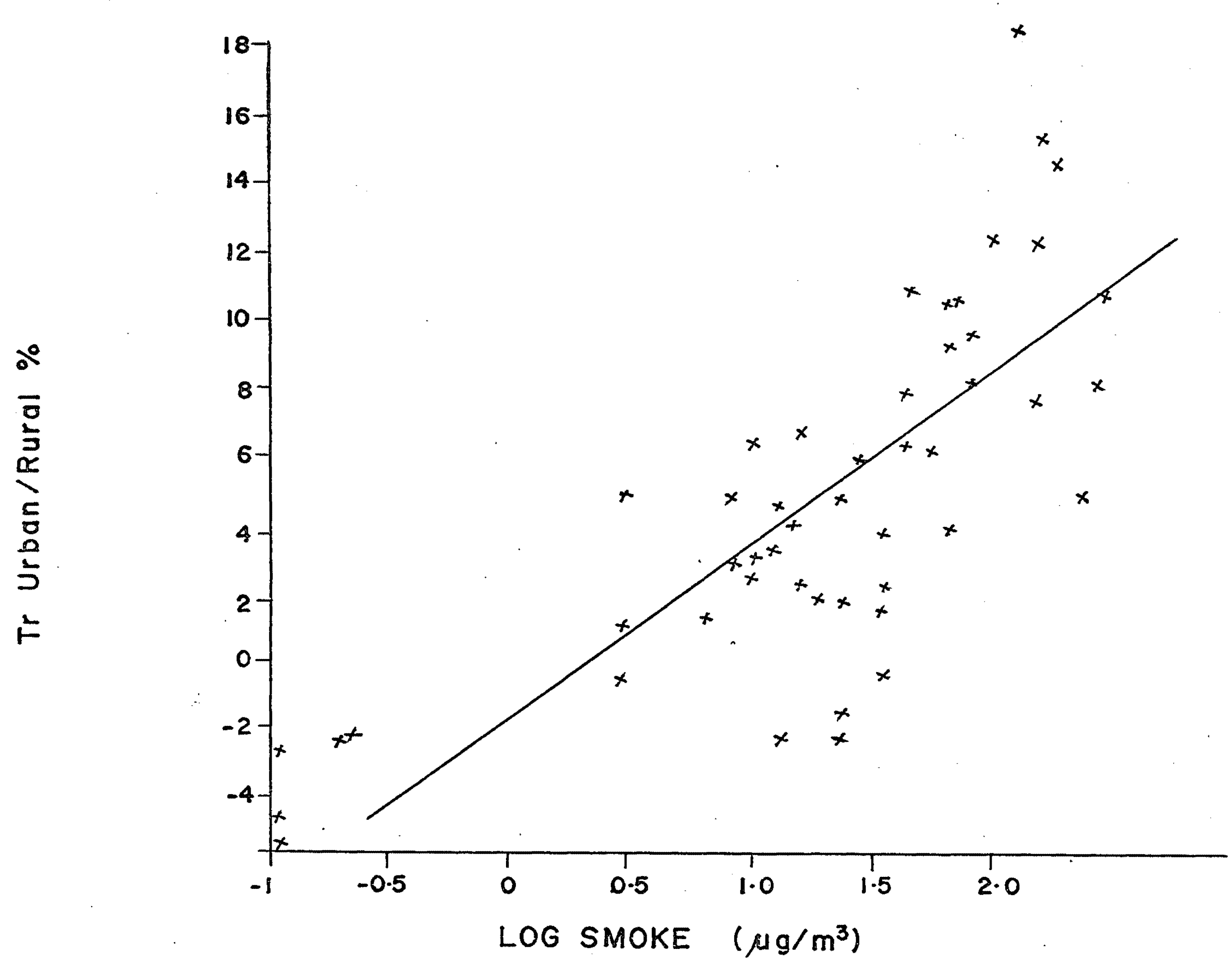
Monteith (1966) stated that for London, a $10\,\mu g/m^3$ reduction in smoke resulted in a 1% increase in $SW\downarrow$. Testing of the regression equation

$$\text{Tr urban/rural } \% = 0.013 + .08457\ S. \qquad \ldots. (4.3)$$

gives a value of 0.8% increase in transmissivity with every $10\,\mu g/m^3$ of smoke decrease. Unfortunately, comparison of these figures with those of Monteith is difficult because they apply to different measures of short wave radiation. Earlier it was shown that urban/rural variations in q were insignificant, and from equation 4.1 it can be seen that a given reduction in Tr will only be equivalent to a reduction in Q if m = 1. For values of m greater than one, corresponding Tr reduction will be smaller than reductions in Q. Thus it appears that the effect of smoke pollution on short wave radiation is at least of the same order in Christchurch as that established in London (given that m is always > 1).

An attempt was made to achieve even better correlations between smoke and Tr urban/rural % by adjusting for solar elevation in the method of Yamashita (1973). Smoke was expressed as S. Cos a (where a is the altitude of the sun), but it was found to make only marginal improvement to the existing correlations.

Figure 4. 3 Relation Between Tr Urban/Rural % and Log Smoke



Tr Urban/Rural %
18
16
14
12
10
8
6
4
2
0
-2
-4
-1
-0·5
0
0·5
1·0
1·5
2·0
LOG SMOKE (µg/m³)

The influence of smoke on atmospheric transmissivities can be seen well illustrated on certain days during the study period. 4 July 1976 was a weekend day which provided the highest recorded day-time smoke levels of the study period. 410 $\mu g/m^3$ was recorded at between 1000 T.S.T. and 1200 T.S.T. Table 4.11 gives the daily trends in transmissivity for both major sites, and the measured smoke amount at the city site for that day. The Tr_R value stays relatively constant throughout the day, while the Tr_U value shows a dip towards the middle of the day, closely paralleling measured smoke observations.

Plate 4.1 is a sequence of five photographs taken on the same day from early morning until 0945 T.S.T., just as pollution levels were beginning to climb and transmissivities reduce in the centre of the city. The Tr urban/rural % at the time of the last photograph amounted to 5%, but was to climb as high as 15% later in the day. The maximum daily mixing depth on this day was only 250 metres which tended to trap pollutants very near to the surface. Unlike most days, the inversion did not break at around T.S.N., with an abrupt drop in smoke levels. Winds were suppressed on this day from 0500 T.S.T. to 1500 T.S.T., and the reason for the continuation of the inversion was probably because of the very low city surface air temperature (6.0°C maximum).

Observations made about the influence of smoke on short wave radiation receipt at the urban surface agree with those of many overseas workers such as East (1968), Probald (1972), Monteith (1966) and Mateer (1961). There is a strong relationship between measured air pollution and radiation attenuation, with the effects becoming greatest in the winter half year when conditions are most conducive to pollution and the solar path length is longer. The relationship of yearly variations in meteorological parameters to Tr through their effect on smoke leads to a consideration of the effect of wind speed and direction on urban/rural transmissivities.

TABLE 4.11

Transmissivities and Urban Smoke Pollution

4 July 1976

Hr to	Tr_U	Smoke Urban ($\mu g/m^3$)	Tr_R	% Urban/Rural
0900	.9486	40	.9129	-3.9
1000	.8421	320	.8867	5.3
1100	.7992	410	.8692	8.8
1200	.7595	410	.8453	11.3
1300	.7478	264	.8603	15.0
1400	.7811	240	.8447	8.1
1500	.8002	80	.8541	6.7
1600	.8305	60	.8545	1.7

Plate 4.1 Photographic Sequence from Port Hills, 4 July 1976.

0745 T. S. T.

0825 T. S. T.

0900 T.S.T.

0915 T. S. T.

0945 T. S. T.

Wind Speed and Direction

Wind speed and direction are important considerations in any discussion of urban/rural differences in transmissivity for not only do they determine dispersion (Chapter 3), but they can also determine the source of atmospheric pollution (Yamashita, 1970).

Table 4. 12 is a summary of regression analysis performed on the relationship between wind speed and atmospheric transmissivities. Percentage transmissivity differences (Tr urban/rural %) show a much stronger relationship with wind speed than to the individual hourly transmissivities at each site. The r values are low, but the large number of observations makes the relationship significant at the .01 level. It appears that because of possible greater influences from atmospheric variables such as vapour pressure, the effect of wind speed on Tr values is insignificant.

Figure 4. 4 shows the negative relationship between wind speed and percentage reduction of urban transmissivity for all winter data. Because of the wide scatter of points, the existence of an exponential decay of reduction ratio with increasing wind speed such as found for Tokyo and Osaka by Nishizawa and Yamashita (1968) is difficult to determine.

One interesting point to be revealed from the summary of regression analysis is the tendency toward negative b coefficients in the relationship between rural transmissivities and wind speeds, an observation which becomes significant at the 0.05 level in the wintertime. This may be because higher winds increase turbidity over the airport in summer with strong, dusty, northwest winds, and in winter the south winds which could bring pollution from the industrial area of Sockburn, Islington and Hornby which lie directly to the south and southwest of the airport.

An example of the local effect that wind can have on variations of atmospheric transmissivity is shown on 1 July 1976. Plate 4. 2 was taken on that day at 1130 T.S.T. and shows the effect of a moderate (11 kt) southwest wind which sprang up approximately 15 minutes prior

TABLE 4.12

Summary of Regression Analysis (Wind Speed)

Dependent Variable	No. Obs.	a	b	r	Significance
Term Tr U/R %	205	5.754	-0.3956	-0.298	.01
Winter Tr U/R %	135	7.7284	-0.44371	-0.3894	.01
Term Tr_U	205	0.7834	0.00234	0.0143	N.S.
Winter Tr_U	135	0.80418	0.00175	0.1124	N.S.
Term Tr_R	205	0.8437	-0.00197	-0.0853	N.S.
Winter Tr_R	135	0.8657	-0.00275	-0.1893	.05

Figure 4.4 Relation Between Tr Urban/Rural % and Wind Speed

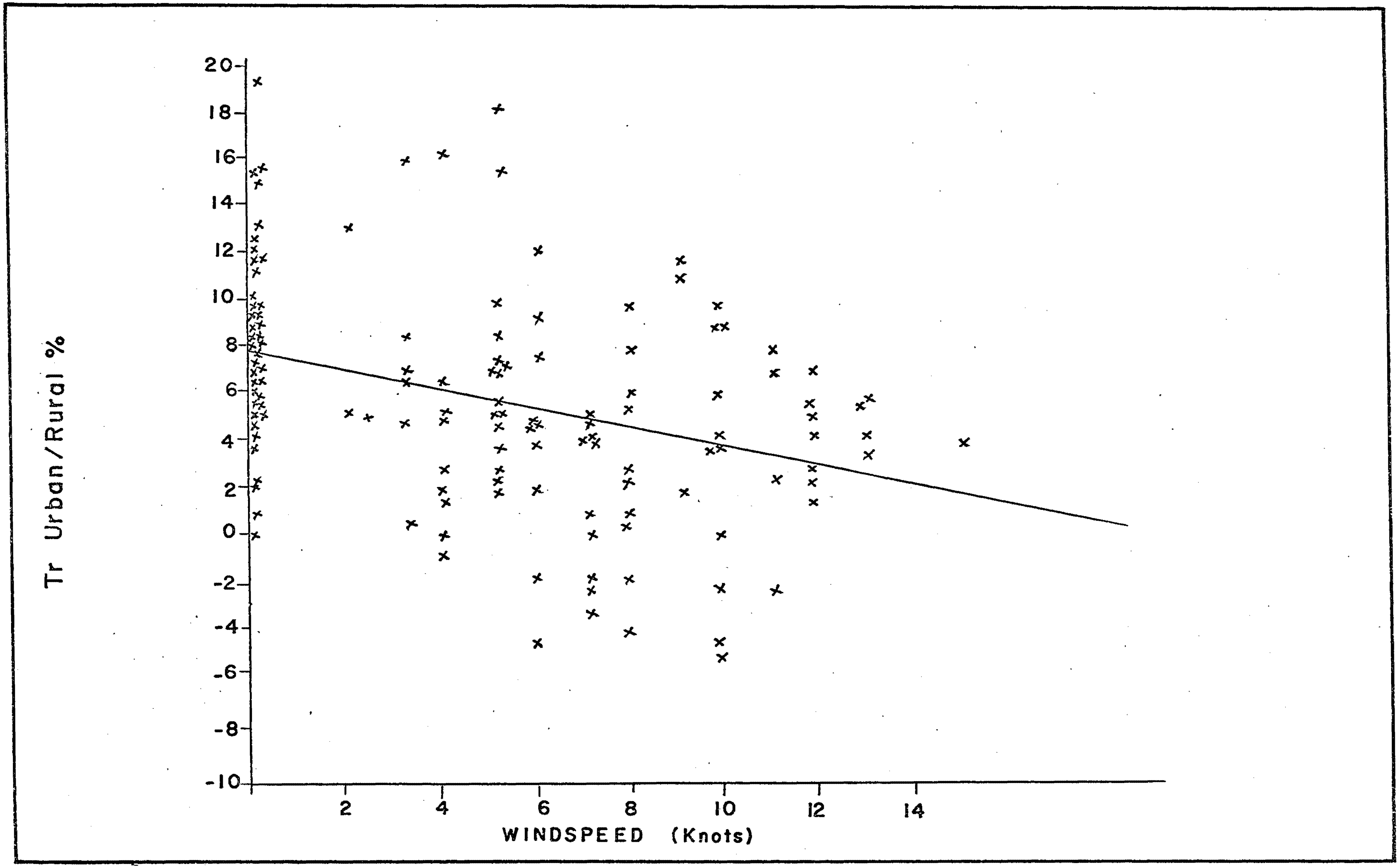
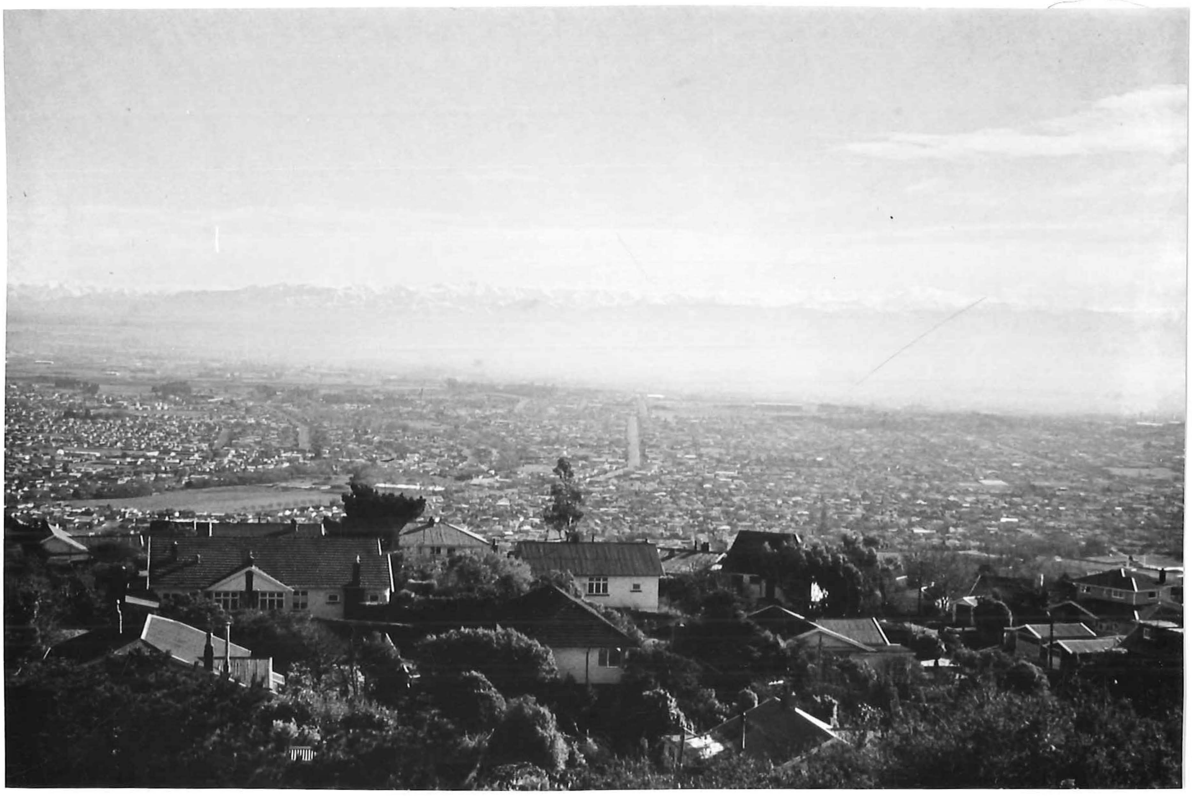

Tr Urban/Rural %
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
2
4
6
8
10
12
14
WINDSPEED (Knots)

Plate 4.2 Effect of Recently Arrived SW Wind on Pollution



to the photograph being taken. Table 4.13 shows the relationship between Tr_U, Tr_R, wind speed and direction, and smoke levels for that day. Note that while cloud amounts were high early and late in the day, at the time of the wind change, cloud amounts were only 1/8. The table clearly indicates the effect that the breeze had on both the radiation and the smoke parameters. The effect of the wind was to almost equalise the Tr values for urban and rural sites after an initial difference of 13.7%.

Nishizawa and Yamashita (1968) also found a relationship between urban reduction ratios and wind direction (and therefore the sector contributing pollutants). Christchurch transmissivity data was examined for several days in June 1976 when the wind direction changed during the day. Wind directions were divided into two sectors, east and south (60^{o} - 240^{o}) and west and north (240^{o} - 60^{o}). This division was used as it was felt that south or east winds would tend to reduce rural transmissivity because polluted air would be blown towards the rural site (see Figure 2.1), while winds from the other sector would maximise any urban/rural difference. Calm conditions were included with the west and north winds as it was felt that these also would inhibit the exchange of polluted air between urban and rural areas.

Table 4.14(a) shows the average hourly urban/rural Tr reductions under winds from either sector for five clear days. An initial reaction would be to accept that wind direction is important in the urban/rural reduction ratio as it either decreases or increases the difference between sites. However, the information should be treated carefully as there is often a diurnal cycle of wind direction. The westerly is often an early morning occurrence (usually katabatic), associated with deep inversions, while the easterly is often an afternoon wind originating after the inversion has broken up and land surfaces have warmed. The former wind is therefore associated with high pollution in the city while the

TABLE 4.13

Relationship of Wind Characteristics to Urban Transmissivities (1.4.76)

Hr to	Tr_U	Tr_R	Tr U/R %	W/s kts	Direction	Cloud 1/8	Urban Smoke $\mu g/m^3$
0900	0.4832	0.5620	-	0	Calm	7	100
1000	0.7632	0.8680	13.7	0	"	2	180
1100	0.7635	0.8500	11.4	0	"	1	165
1200	0.7935	0.8498	7.0	11	210	1	120
1300	0.8133	0.8413	3.4	12	190	1	25
1400	0.8110	0.8480	4.6	10	190	2	15
1500	0.6925	0.4398	-	7	190	5	15
1600	0.4253	0.4138	-	8	220	5	25

TABLE 4.14

(a) Percent Reduction in Tr Under Different Wind Directions

	West and North	East and South
June 11	6.25	0.19
12	9.03	3.42
13	12.0	4.0
19	7.7	3.64
25	5.6	3.12
$\bar{X}$	8.12	3.05

(b) Rural Tr Under Different Wind Directions

	West and North	East and South
June 11	.9288	.8390
12	.8845	.8239
13	.8100	.8000
19	.9069	.8798
25	.8709	.8701
$\bar{X}$	.8802	.8425

% Difference = 4.5

other wind is associated with lower pollution. The reason for the decreasing difference may therefore have little to do with pollution arriving over the rural site.

An examination of Tr_R for the same periods (Table 4. 14(b)) does indicate that there is some sort of effect on rural transmissivity under different wind directions. This suggests that at least part of the different reductions shown in Table 4. 14(a) is due to wind direction rather than only the associated atmospheric stability factors. The differences shown in Table 4. 14(b) are significant at the 0. 05 level in t-test.

Yamashita (1973) in Toronto, described the effect of winds pushing the urban pollution dome toward the sun and away from the sun in increasing or decreasing urban/rural differences in radiation. He believed that the reason for this was the solar path length through the pollution dome. Unfortunately this could not be examined for the Christchurch case, as the winds which push the pollution dome towards the sun (southerlies) are the same as those which spread pollution over the rural site. However, it was possible to examine Tr_U under southerly and northerly winds under days when pollution was similar. Table 4.15 shows data from two days, 11 June and 13 June, the winds being light northeast and southwest respectively. Despite the fact that pollution levels are higher over much of the day of 11 June, transmissivities are at all times higher than on 13 June. The reason for this can probably be traced to the repositioning of the urban pollution dome towards the sun on 13 June because of the winds. This would have resulted in a longer solar path length through the pollution dome, and hence greater attenuation. The switch from southerly winds to northeast after 1400 hrs on 13 June resulted in an immediate improvement in transmissivity as the pollution dome shifted away from the sun again.

TABLE 4.15

Urban Transmissivities Under Northeast and Southwest Winds

11 June 1976

Hr to	Tr	Wind Direction	Smoke $\mu g/m^3$
0900	0.9928	000	200
1000	0.8704	360	250
1100	0.8234	000	140
1200	0.8379	030	140
1300	0.8190	040	16
1400	0.8206	060	12
1500	0.8094	060	5
1600	0.8166	050	10

13 June 1976

Hr to	Tr	Wind Direction	Smoke $\mu g/m^3$
0900	0.6000	240	26
1000	0.6537	210	120
1100	0.7448	260	56
1200	0.8023	190	40
1300	0.7814	180	40
1400	0.7755	000	35
1500	0.8010	030	10
1600	0.8182	050	10

Mixing Depth

One other meteorological factor which affects pollution occurrence, therefore indirectly influencing the SW$\downarrow$ at the surface, is atmospheric stability. Mixing depth as a measure of atmospheric stability defines the maximum height that particles will rise according to natural thermal turbulence. Given that day to day outputs of pollutants vary little, then it can be suggested that a certain mixing depth determines smoke concentrations, and hence will determine radiation attenuation.

The summary of regression analysis for transmissivity and mixing depth is shown in Table 4.16. The relationships in all cases are as would be expected, with Tr urban/rural % increasing with decreasing mixing depth and site Tr values increasing with increasing mixing depths. Correlation is in general poor except for Tr_U which shows a trend significant at the 0.01 level. The major problem with this analysis is the small sample, referring only to daily data from clear days. The measure also only uses a maximum urban mixing depth for each day, which may bear little relationship to mixing depths at other times of the day (temperatures at the surface fluctuate widely). Because of this the actual concentrations of smoke at certain times of the day may not be indicated successfully by the one daily measure. However, in the absence of more regular radiosonde profiles, it is not possible to successfully determine mixing depths on a more frequent basis. It is probable that, had an analysis of mixing depths been undertaken on a more regular basis, a considerable amount would have been added to the explanation of variance.

One particularly interesting point in Table 4.16 is the significant (0.05) relationship between winter Tr_R and daily maximum mixing depth for that site. The reason for this is not entirely clear as smoke levels would be expected to be too low to have an appreciable

TABLE 4.16

Summary of Regression Analysis (Mixing Depth)

Dependent Variable	No. Obs.	a	b	r	Significance
Term Tr U/R %	28	6.354	-0.00109763	-0.2510	N.S.
Winter Tr U/R %	15	6.713	-0.001443	-0.3097	N.S.
Term Tr_U	28	0.8045	0.0000189	0.27833	N.S.
Winter Tr_U	15	0.89121	0.0000473	0.6538	.01
Term Tr_R	28	0.8342	0.0000243	0.1974	N.S.
Winter Tr_R	15	0.89564	0.0000341	0.52617	.05

effect on the Tr values. However, it is possible that there is some urban influence at the rural site under conditions particularly favourable for pollution concentration.

In the absence of more frequent mixing depth values, it is not possible to illustrate daily trends with transmissivity characteristics. The effect of what probably is the break up of inversions has already been documented in this chapter.

Vapour Pressure

One final pollution independent variable that should be mentioned in any consideration of radiation differences is vapour pressure. Table 4.17 shows the relationship between transmissivity characteristics and vapour pressure. For the examination of Tr urban/rural % against vapour pressure characteristics, the vapour pressure at the rural site was expressed as a proportion of urban vapour pressure. This relationship was not significant, while the relationship between individual Tr values and vapour pressure recorded at that site was significant at the 0.01 level for both urban and rural sites. In this case the relationship was a negative one with higher vapour pressures reducing atmospheric transmissivity above each site, due to the interception of the solar beam in the lower atmosphere by water vapour. Therefore, the observation made earlier in this chapter about the higher transmissivities of winter being related to lower amounts of water vapour in the atmosphere appears to be supported.

An examination of the effect of vapour pressure on winter transmissivity indicates no significant relationship, probably because of the low fluctuation of vapour pressure within the one season.

It appears that while vapour pressure is important in the transmission of SW$\downarrow$ on the long term through its seasonal variation (up to 7 mb at each site in this study), at the short term and on the city-wide scale the importance is considerably reduced because of the small differences in vapour pressure involved (always less than 2 mb).

TABLE 4.17

Summary of Regression Analysis (Water Vapour)

Dependent Variable	No. Obs.	a	b	r	Significance
Term Tr U/R %	205	4.1894	0.004607	0.02305	N.S.
Term Tr_U	205	0.8427	-0.005266	-0.26286	.01
Winter Tr_U	50	0.8338	-0.01032	-0.0953	N.S.
Term Tr_R	265	0.8968	-0.006997	-0.3260	.01

The Relative Importance of Variables in the Determination of Tr urban/rural %.

The interrelationships between the four independent variables and the dependent variable (Tr urban/rural %) were considered using 50 hourly winter observations. This gave the correlation matrix outlined in Table 4. 18(a). The coefficient of multiple correlation was 0. 773 and application of an F-test showed the relationship to be significant at the 0. 01 level.

Application of partial correlations to individual independent variables suggested the order for entry into the stepwise correlation which is shown in Table 4. 18(b). This indicates the dominant effect that smoke has in the statistical explanation of variation in Tr urban/rural %, explaining 57. 4% of variance on its own. Although wind speed is quite highly correlated with Tr urban/rural %, it adds only 1. 3% more to the variance because of its close relationship to smoke. Surprisingly, vapour pressure enters the stepwise regression next, before mixing depth, presumably because it is relatively independent of smoke.

It appears from this analysis that $SW\downarrow$ in Christchurch is influenced by atmospheric pollution to the almost total exclusion of any other variables discussed in the study. It is difficult to think of any other variables which may have any greater impact on the measured urban/rural transmissivity differences than the ones already used.

MODELLING OF INCOMING SOLAR RADIATION

Up to this point in the chapter, relationships have been of a purely statistical nature only although some discussion of the reasons underlying these relationships has been attempted. One method of more firmly establishing the existence of mechanisms is to formulate them in mathematical terms. This should then allow prediction and

TABLE 4.18

(a) Multiple Correlation Matrix for the Explanation of Winter Urban/Rural Transmissivity Differences

Vapour pressure urban/rural %	Urban Mixing depth	Urban excess Log smoke	Wind Speed	Tr urban/ rural %	
1.000	-0.204	0.160	0.074	0.019	Vapour pressure urban/rural %
	1.000	-0.167	0.065	-0.166	Urban mixing depth
		1.000	-0.574	0.758	Urban excess Log smoke
			1.000	-0.527	Wind Speed
				1.000	Tr urban/ rural %

(b) Independent Variable Contribution to % Urban Transmissivity Reduction

Independent Variable	Total Explained Variable	Variance Explained by New Variable	F Ratio	Significance
Log smoke	57.4	57.4	68.829	.01
Wind speed	58.7	1.3	33.443	.01
U/R vapour pressure	59.4	0.7	22.437	.01
Mixing depth	59.7	0.3	16.704	.01

and observation of the effect of changes in potential causal variables. In this study it has been suggested that smoke and vapour pressure were the variables most directly affecting atmospheric transmissivity.

A simulation model which should allow analysis of these effects is the surface climate simulator developed by Outcalt (1972) after earlier work by Myrup (1969). The part of Outcalt's programme dealing with SW$\downarrow$ was used for this thesis and is listed in "SUNGEN" in Appendix IV.

The radiation climatology generator employs the partially empirical equation of Brooks (1959) for derivation of Tr which is given by,

$$Tr = \exp\left(-0.089\,(pm/1013)^{.75} - 0.174\,(wm/20)^{.6} - 0.083\,(dm)^{.9}\right) \qquad \ldots\ (4.4)$$

where, Tr = transmittance of whole spectrum direct beam solar radiation.

p = air pressure (mb)

w = water vapour (mm)

d = dust (particles/cc)

m = optical air path.

The above equation allows explanation of the effect of altitude, water vapour and dust on the transmission of direct beam solar radiation. However, its one drawback is that it was developed for "natural" atmospheres, therefore its application to the Christchurch urban atmosphere may not be entirely successful.

The simulation was applied to atmospheric data from both Christchurch urban and rural sites for 4 July 1976, a day of great variation in measured pollution. All moisture characteristics were converted to precipitable water vapour using the Reitan equation;

$$\log \text{natural } w\,(cm) = -0.981 + 0.0341\,D \qquad \ldots\ (4.5)$$

where, D = surface dew point (^{o}F)

(Munn, 1970)

Smoke amounts were converted to particles/cc at the ratio of 1 particle for every 100 $\mu g/m^3$ of smoke. This was done assuming an average particulate size of 0.5 u, a not unreasonable assumption of particulate size for urban atmospheres (Pullen, pers. comm.).

Table 4.19 shows the agreement between predicted and measured (bracketed) incoming SW characteristics. It can be seen that both direct beam radiation and Tr agree well (Tr 0.4%, difference) but the diffuse component is far too high, giving a total SW↓ considerably larger in the simulation than observed. The dominant effect of increased particulates can be seen with the considerable drop in the proportion of the extra-terrestrial SW↓ received as direct beam for both observed and predicted values between 0900 and 1000 T.S.T.

A similar treatment of data from the rural site had even less agreement between observed and predicted SW↓. Direct beam and Tr values predicted from input data were far higher than those actually measured, and diffuse beam radiation was equally under-estimated.

Possible reasons for these deviations can be put forward in the absence of detailed analysis. In the case of the rural simulation the high direct beam and low diffuse beam components compared with those measured are a possible result of higher turbidity at altitude than is predicted from surface measurements. Because of the rural site's proximity to the city, the possibility of an urban pollution dome extending to that site cannot be discounted.

The source of the model/measured deviation for the urban site appears to be in the diffuse/backscatter ratio at times of high pollution. With particles/cc less than 0.6, agreement is quite good. It appears that the model, which uses dust scattering occurring in pure, clear air (Brooks, 1959, p. 35), predicts much more forward scatter than actually occurs in the Christchurch urban situation. The size and nature of particulates occurring in the Christchurch urban atmosphere

TABLE 4.19

Solar Radiation Simulation 4 July 1976

Urban Site

(Measured values in brackets)

Time	Dust/cc	ppt water (mm)	w/m^2					Tr
			Ex-Terr.	Direct	Diffuse	Backscatter	Total	
0800	0.4	7.26	129.0	26.5 (68.72)	22.0 (14.1)	1.2	49.6 (92.3)	0.8476 (0.985)
0900	0.6	8.21	396.8	182.6 (165.8)	38.9 (28.9)	3.2	224.8 (194.7)	0.906 (0.895)
1000	3.4	10.5	602.3	187.2 (215.3)	153.9 (36.4)	13.0	354.2 (251.7)	0.7788 (0.820)
1100	4.1	8.73	731.5	246.8 (243.9)	186.1 (45.0)	16.5	449.5 (288.9)	0.775 (0.774)
1200	4.1	9.28	775.6	273.5 (242.7)	190.2 (53.0)	17.0	480.8 (295.6)	0.781 (0.753)
1300	2.64	11.16	731.5	302.2 (231.1)	139.0 (50.8)	12.5	453.9 (281.9)	0.835 (0.764)
1400	2.4	9.28	602.3	230.8 (198.7)	122.6 (41.7)	10.7	364.3 (239.9)	0.832 (0.79)
1500	0.8	11.16	396.8	162.2 (116.0)	48.9 (29.0)	3.9	215.1 (145.1)	0.880 (0.815)
1600	0.6	9.87	129.0	20.0 (32.0)	29.1 (13.7)	1.6	50.8 (45.0)	0.818 (0.820)
								0.8102 0.8248

apparently either increases absorption of SW$\downarrow$ or increases the ratio of backscatter to forward scatter of diffuse beam.

While this has been a limited test only, the good agreement between predicted Q and Tr at the urban site lends weight to the suggestion that smoke especially, and water vapour, are the important causes of variation. On the other hand, the diffuse beam generator is less successful, perhaps because of the effect of varying particle size, and should be modified for the urban Christchurch situation.

CONCLUSIONS

An examination of urban/rural SW$\downarrow$ radiation characteristics for Christchurch gives the following major points:

1) There was an average daily total SW$\downarrow$ urban/rural difference of 14.9% over clear days in the study period, with individual daily differences as high as 30%. The trend was towards higher attenuation at lower solar elevations, both on a yearly and daily basis and when pollution was highest.

2) Diffuse beam SW$\downarrow$ showed only slight and statistically insignificant differences between urban and rural sites, with an increasing urban excess towards winter probably being related to urban pollution.

3) Urban and rural transmissivity values both show an increase towards the winter half year, related to a decreasing water vapour content of the atmosphere. However, Tr urban/rural % differences tend to increase towards winter in response to the increasing urban pollution.

4) A very clear relationship between smoke and urban/rural differences in transmissivity was established in regression analysis. An average 0.8% increase in transmissivity with every 10 $\mu g/m^3$ decrease in smoke was observed.

5) Other atmospheric variables were not nearly as closely related to Tr urban/rural % differences, but variables such as wind direction and vapour pressure were found to be important on a daily and long term scale respectively.

6) Stepwise regression confirmed the dominant influence of smoke in explaining urban/rural differences where it contributed 57.4% of the variance in $Tr_{U/R}$, with the other variables of wind speed, mixing depth and vapour pressure adding only another 2.3%.

7) Application of computer simulation to data from the urban site substantiated the important effect of smoke on incoming SW$\downarrow$, and suggested that the diffuse radiation component was also considerably modified by the type of pollutants in the urban atmosphere.

CHAPTER FIVE

URBAN/RURAL INCOMING LONG WAVE RADIATION CHARACTERISTICS

INTRODUCTION

It is the major concern of this chapter to discuss the absolute variation of LW$\downarrow$ between the two major sites, and to outline probable causes of this variation. Such an examination of LW radiation characteristics involves a consideration of the effect of atmospheric temperature, water vapour, particulates, wind speed and direction and atmospheric stability.

Any consideration of LW$\downarrow$ should involve a discussion of the effect of SW$\downarrow$, as this is the ultimate source of the energy manifested in LW$\downarrow$. One important point that should be borne in mind in any discussion of LW$\downarrow$, is the effect that the SW$\downarrow$ component has in the equation for the derivation of LW$\downarrow$ during daylight hours (equation 2. 3). Subtraction of SW$\downarrow$ from the rest of the equation has an important bearing on the computed LW$\downarrow$. The effect of a high SW$\downarrow$ component is to lessen the LW$\downarrow$ holding all other factors constant. Problems arise in that this is what is expected in the literature of urban climatology. In areas of high attenuation of SW$\downarrow$ there is an increase of the LW$\downarrow$ component due to absorption and reradiation. The difficulty arises when deciding whether any LW$\downarrow$ increase or decrease is due to mechanical computation, or physical fact.

The emphasis placed on reliable calibration of all instrumentation in this study means that, within the error of measurement, confidence can be placed in any measured differences. The problem described above does not arise for night readings, and as subsequent results will show, similar LW$\downarrow$ characteristics hold for both day and night.

URBAN/RURAL LW↓ DIFFERENCES

A statistical analysis of the LW↓ data from the total record for the two sites was undertaken on the two hourly values by division of the data into clear, partly cloudy and overcast conditions. For each day type, a two tailed t-test was performed on a standard 100 pair sample, in order to obtain a measure of the statistical significance of urban/rural LW↓ differences under any cloud cover type. Clear weather data was found to have significant differences at the 0.001 level, while the partly cloudy and overcast data was significant at the 0.2 level, and not significant respectively. It is felt that this is because the presence of increasing amounts of cloud in the sky, with warmer radiating temperatures than clear sky, would tend to mask any urban/rural differences.

Analysis in this thesis concentrates on LW↓ data from clear days only for the above reasons. The criterion for selection of days for analysis is even more demanding than was the case for SW↓ , because the presence of cloud anywhere in the sky can affect LW↓ , while SW↓, particularly direct beam, is dominantly affected by cloud only in the direction of the sun. Only observations of $<1/8$ cloud were included in this analysis, which restricted the number of sample days to 14. Most of these days came from the winter period of the study which seemed to be less affected by cloud than any other period. On additional days which were $<1/8$ cloud part of the time, data has been used in regression work, but is not discussed in this section.

Table 5.1 is a table of daily average LW↓ for the 14 clear days in this study. There is a seasonal variation in LW↓ for both sites and this results indirectly from seasonal SW↓ variation. LW↓ is dependent on atmospheric emittance, given by;

TABLE 5.1

Daily Average LW$\downarrow$ by Site (w/m^2)

Date	LW Urban	LW Rural	U/R % Diff.	% Diff. by Season	Signif. t-test
24.2	333.1	317.5	4.9		
25.2	341.9	332.0	2.9		t = 3.916
15.3	321.6	295.2	8.7	4.86	
17.3	327.5	315.6	3.7		Signif. = .001
18.3	339.91	326.5	4.1		
22.4	298.7	269.5	10.8	8.15	t = 5.203
26.4	322.1	305.2	5.5		Signif. = .001
11.6	281.3	251.3	11.9		
12.6	273.1	247.6	10.0		
13.6	281.4	263.6	6.3		t = 9.616
19.6	284.9	253.1	12.5	11.24	
26.6	286.8	238.6	20.2		Signif. = .001
29.6	296.1	268.8	10.1		
30.6	283.2	262.8	7.7		

$\overline{X} = 8.52$

$$LW\downarrow = \epsilon \sigma T^4 \qquad \ldots.(5.1)$$

where, T = Temperature (^oK)

σ = Stefan Boltzmann constant

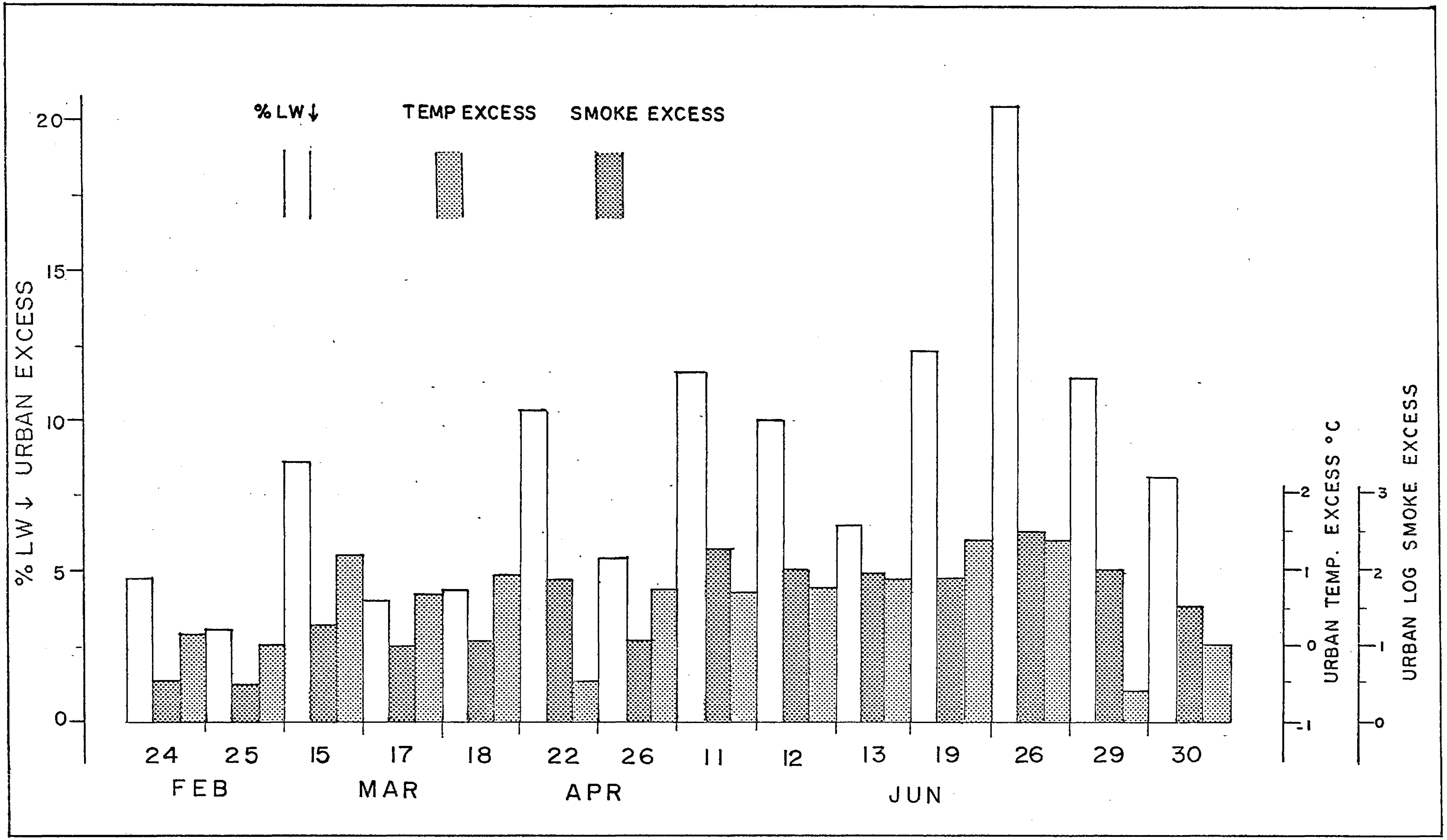
ϵ = effective atmospheric emissivity.

The atmospheric emissivity is dependent to a certain extent on the surface vapour pressure and also the hydrolapse conditions of atmosphere (Le Drew, 1975). Summer conditions produce greater LW$\downarrow$ because higher SW$\downarrow$ amounts raise atmospheric temperatures (directly contributing to LW$\downarrow$), and these higher temperatures allow a considerable amount more water vapour to be absorbed into the atmosphere (Chapter 3).

Apart from the trend towards lower LW$\downarrow$ in the winter months in Table 5.1, an urban/rural trend is also evident. There is an urban excess LW$\downarrow$ at all seasons, but with differences becoming greater in the winter half year. The average LW$\downarrow$ urban excess on clear days was 8.52%, with a highest daily excess on 26 June. The only comparable data obtaining in the literature is an 11% urban excess measured over 160 hrs in Hamilton, Ontario, by Rouse and McCutcheon (1972). In their study, the highest hourly excess measured was 66%, compared with a maximum 39.6% for this study on 26 June.

The difference between LW$\downarrow$ radiation readings at each site in this study was significant at the 0.001 level for all three seasons, the criteria being exceeded most markedly in the winter season. The possible reasons for the urban/rural differences in LW$\downarrow$ revealed in this study will be discussed in depth towards the end of this chapter. However, at this point, a simple plot (Figure 5.1) of daily urban percentage excess LW$\downarrow$ (LW$\downarrow$ urban/rural %) against urban smoke $\log_{10}$ and urban temperature excess indicates a definite relationship, particularly between smoke and LW$\downarrow$. While there appears to be some relationship between LW$\downarrow$ and temperature excess, it is not as good as that with smoke, and on occasions LW$\downarrow$ urban/rural % peaks where the urban excess temperature has dipped.

Figure 5.1 Daily Average Urban LW$\downarrow$ Excess in Relation to Urban Excess Smoke and Temperature


% LW↓
TEMP EXCESS
SMOKE EXCESS
% LW↓ URBAN EXCESS
20
15
10
5
0
24
25
15
17
18
22
26
11
12
13
19
26
29
30
FEB
MAR
APR
JUN
URBAN TEMP. EXCESS °C
2
1
0
-1
URBAN LOG SMOKE EXCESS
3
2
1
0

The daily variations in LW↓ are shown in Table 5.2. In winter the rural site shows a fairly constant LW↓ throughout the day (range 16.4 w/m^2), a phenomenon common to other rural observations of LW↓ (Monteith and Szeicz, 1961; Sanderson, 1974). By comparison, LW↓ at the urban site shows a peak just before solar noon, which gives a maximum urban excess LW↓ at this time. Winter urban LW↓ shows a second daily peak excess over rural LW↓ in the evening after a period of similar readings in the late afternoon. The variation in LW↓ daily at the urban site is several times that at the rural site (58 w/m^2). Summer daily LW↓ trends show a much lower peak in urban/rural radiation excess, probably because of the lower daily variation of LW↓ of the urban site. However, there is once again a detectable tendency for a peak in urban excess LW↓ at around T.S.N., indicating the presence of a LW↓ inducing property in the urban atmosphere.

Table 5.2 also indicates that the urban LW↓ excess continues into nightime hours, although the difference is not as significant as the daytime LW↓ excess. Nightime LW↓ excess in summer amounts to 3.2% and to 10.9% in winter, less than the 6.1% and 14.5% excess readings for LW↓ during daytime. The continuation of LW↓ urban excess into the evening was not observed by Rouse et al. (1973), but Oke and Fuggle (1972), in a series of nightime observations in Montreal, found an urban excess which was usually less than 5%. It should be noted that Rouse et al. carried out their investigations under summer conditions. Corresponding LW↓ excesses in this study were low ($<$ 3% on average).

A simple comparison of urban LW↓ excess with urban smoke and temperature excess (Table 5.3) indicates a possible relationship between LW↓ and smoke. The daytime peak in smoke is marked by a greater proportionate increase in LW↓ excess than the peak at night, despite the fact that smoke amounts are greater at night. This indicates the

TABLE 5.2

Seasonal Hourly LW↓ Radiation Values

	Winter			Autumn			Summer		
	$LW\downarrow_U$	$LW\downarrow_R$	U/R %	$LW\downarrow_U$	$LW\downarrow_R$	U/R %	$LW\downarrow_U$	$LW\downarrow_R$	U/R %
00-02	282.1	239.3	17.9	299.5	289.9	3.3	320.5	312.3	2.6
4	278.8	251.4	10.9	305.5	282.5	8.1	330.7	312.9	5.7
6	278.9	249.5	11.8	319.5	282.7	13.0	325.2	313.6	3.7
8	286.8	249.6	14.9	312.0	273.7	14.0	327.0	303.4	7.8
10	312.2	255.7	22.1	335.9	270.9	24.0	320.5	306.7	4.7
12	303.9	252.7	20.3	300.2	276.4	8.6	316.7	289.6	9.3
14	291.5	256.6	13.61	312.9	300.0	4.3	329.0	308.5	6.9
16	254.2	249.7	1.8	309.1	306.0	1.0	345.0	331.7	4.0
18	266.6	249.9	6.7	308.5	296.0	4.2	343.0	329.0	4.2
20	276.6	252.0	9.8	307.0	291.9	5.2	332.7	323.7	2.9
22	263.9	239.9	10.0	300.1	290.6	3.3	335.5	328.0	2.3
22-24	271.7	248.6	9.3	300.0	290.7	3.2	332.5	325.0	2.3
Range	58.0	16.4		36.4	35.1		29.0	36.0	

TABLE 5.3

Comparison of Urban Winter LW$\downarrow$ Excess

with Smoke and Temperature

Hr	Urban LW$\downarrow$ % Excess	Smoke (urban excess) $\mu g/m^3$	Temperature (urban excess) ^{o}C
00-02	17.9	92	0.9
4	10.9	38	1.8
6	11.8	23	0.5
8	14.9	34	-1.2
10	22.1	137	-1.3
12	20.3	97	-1.3
14	13.6	28	-0.1
16	1.8	41	-0.3
18	6.7	175	-0.1
20	9.8	365	0.9
22	10.0	278	3.0
22-24	9.3	100	2.8

probable effect of solar radiation on the pollution blanket, causing absorption and long wave reradiation. At night, after the loss of residual heat from solar radiation, it is simply the effect of relatively warmer layers of pollutants blocking out the cooler sky which gives the urban excess. In this brief example, temperature does not appear to follow the urban excess LW↓ , but seems to do the opposite. This appears to be because the period in the late morning when urban LW↓ excess is greatest (and smoke pollution is high), is the time of day when the rural area is warming most quickly (Chapter 3).

COMPARISON OF URBAN/RURAL TOTAL INCOMING RADIATION

Before a full consideration of the possible causes of urban excess LW↓ is made, it would be useful to consider the total radiant income for both sites, as this could help decide the mechanism behind increased LW↓ in urban areas.

Two days are examined, representative of the summer season and winter season respectively. Table 5.4 shows the total incoming radiation for both sites on 19 June and 25 February. The ratio of urban to rural total radiation is also shown for both days. 19 June shows a marked rural deficit in the income of total radiation during the night (LW↓ only), but over the daylight hours the ratio of total radiation for both sites is much closer, generally between 0.96 and 1.04. 25 February shows a ratio near unity during the day, with a slight tendency for urban gain in total radiant income at night.

It is therefore obvious that the generally lower urban SW↓ is almost completely balanced by an increased LW↓ during the day, which supports the observations of Rouse <u>et al.</u> (1973) for Hamilton, Ontario. Unlike Rouse <u>et al.</u>, this study found a substantial, true urban energy gain at night in winter, so that the daily total shows an urban energy excess (6% greater than the rural site). This may have implications for the

TABLE 5.4 Ratio of Urban/Rural Total Radiation

19 June 25 February

	Urban LW↓ + SW↓	Rural LW↓ + SW↓	Urban/Rural	Urban LW↓ + SW↓	Rural LW↓ + SW↓	Urban/Rural
00-01	292.1	256.1	1.14	334.0	331.2	1.01
2	288.7	251.5	1.15	331.5	330.1	1.00
3	296.5	251.7	1.18	329.8	327.1	1.01
4	296.7	258.8	1.15	330.1	325.1	1.01
5	299.0	264.7	1.13	335.0	330.1	1.01
66	301.4	368.3	1.12	346.9	378.6	1.03
7	301.1	277.2	1.09	456.9		
8	303.4	283.8	1.07	573.8	559.3	1.02
9	383.8	353.5	1.08	753.8	769.6	1.00
10	463.4	453.2	1.02	971.7	1008.6	0.96
11	524.8	546.5	0.96	1041.2	1073.1	0.97
12	589.1	598.8	0.98	1127.5	1193.1	0.95
13	610.8	605.9	1.01	1103.5	1126.0	0.98
14	591.7	581.2	1.02	1093.3	1132.4	0.97
15	520.7	510.5	1.02	983.0	1003.1	0.98
16	419.3	403.3	1.04	883.8	921.8	0.96
17	325.4	349.7	0.93	626.0	645.4	0.97
18	276.4	266.9	1.03	518.0	526.0	0.98
19	277.7	266.9	1.04	426.6	430.9	0.99
20	276.9	265.3	1.04	356.6	347.7	1.02
21	278.9	264.6	1.06	357.6	355.5	1.00
22	279.7	260.3	1.07	359.1	350.1	1.02
23	278.7	256.4	1.09	368.6	349.1	0.99
23-24	283.8	268.8	1.06	349.7	340.7	1.03
			X 1.06			X 0.96

urban "heat island", though it seems unlikely that the absolute energy excess would be enough to give recorded temperature excesses.

AN EXAMINATION OF FACTORS INVOLVED IN URBAN/ RURAL DIFFERENCES IN LW↓

This section attempts to establish the tentative relationships suggested up to this point on a firmer basis, by using both simple and multiple correlation and regression analysis. The analysis looks at variables which theoretically can contribute to differences in LW↓ across the urban areas, including those having a direct influence on LW↓ , such as pollution, temperature and vapour pressure, and those such as wind speed and direction and atmospheric stability which can have an indirect effect through their influence on other variables. At the end of this section attempts are made with the aid of simple LW↓ prediction equations, to develop an overall hypothesis which will explain the observed variations in LW↓.

Smoke Pollution

Correlation of up to 160 observations of urban smoke excess ($\log_{10}$) and measured LW↓ urban percentage excess (LW↓ urban/rural %) produced the summary of regression table shown in Table 5. 5. Both term and winter only LW↓ urban/rural % show a strong correlation with smoke, significant at the 0. 01 level. The correlation was best for the winter term with almost 30% of the variance in the dependent variable explained. This follows from the seasonal trend in smoke concentrations that has been observed.

Figure 5. 2 shows the strength of the relationship between LW↓ urban/ rural % and log smoke, where the equation of best fit is,

$$\text{LW}\!\downarrow \text{urban/rural \%} = 7.530 \log^{S} - 2.373 \qquad \ldots. \; (5.2)$$

Correlation of winter $\text{LW}\!\downarrow_U$ showed no significant relationship with log smoke for that site; therefore it seems likely that LW↓ at the individual location is dependent more on the other variables expressed

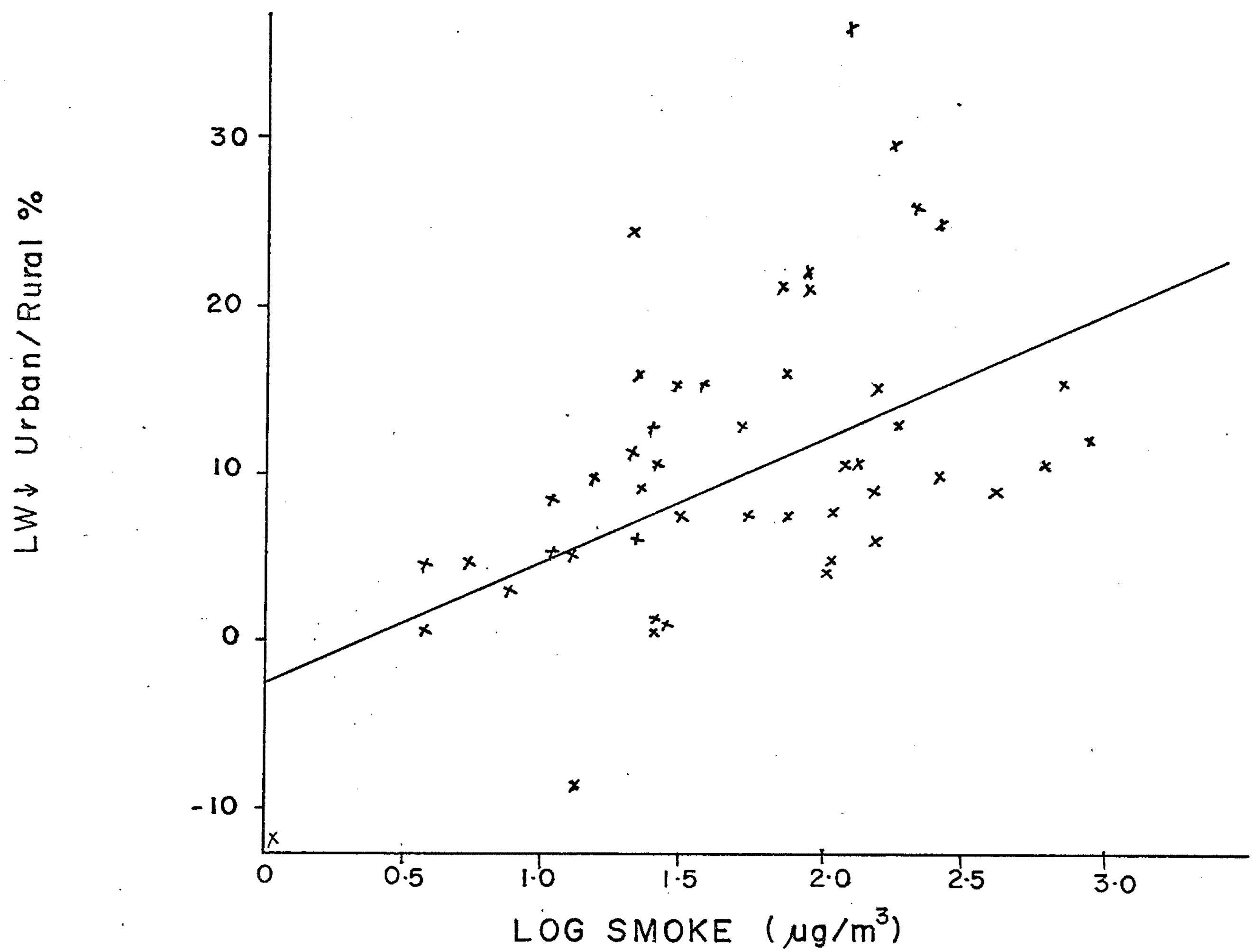
TABLE 5.5

Summary of Regression Analysis

(Log Smoke)

Dependent Variable	No. Obs.	a	b	r	Significance
Term LW↓% urban excess	160	-3.5107	4.8977	0.4899	0.01
Winter LW↓% urban excess	50	-2.373	7.530	0.5222	0.01
Winter LW↓ urban	50	212.609	0.05195	0.001748	N.S.

Figure 5.2 Relation Between LW↓ Urban/Rural % and Log Smoke



LW↓ Urban/Rural %
30
20
10
0
-10
0
0·5
1·0
1·5
2·0
2·5
3·0
LOG SMOKE (μg/m³)

in the Brunt equation (water vapour and temperature). This hypothesis is tested in later analysis. Because of a lack of smoke data for the airport site and the low number of sample days, a correlation between $LW\downarrow_R$ and log smoke was not attempted.

Examples of the strong correlation between urban smoke excess and incoming long wave radiation have already been shown and discussed (Table 5.3). The relationships will not be further discussed here.

Temperature

The relationship between $LW\downarrow$ and temperature is potentially complex and some disagreement on this has appeared in the literature. Some authors, for example Oke and Fuggle (1972) have suggested that $LW\downarrow$ increases in urban areas are merely a result of urban temperature excesses caused by factors other than atmospheric absorption of $SW\downarrow$ and $LW\uparrow$. Other authors, for example Atwater (1971) believe that urban pollution can absorb both $SW\downarrow$ and $LW\uparrow$, hence increasing temperatures of particulates over urban areas and indirectly affecting $LW\downarrow$.

Table 5.6 is a summary of regression of screen temperature and $LW\downarrow$. It would be expected from theoretical considerations in the Stefan Boltzmann relation, that there would be a positive relationship between higher temperatures and $LW\downarrow$ both in terms of measurements at individual sites and in terms of urban excesses in these variables. It is only the individual sites which exhibit this relationship, and even then only poorly. The urban site shows a relationship significant at the 0.02 level where,

$$LW\downarrow_U = 320.547 + 1.034\ T^{o}C \qquad \ldots. (5.3)$$

Using this equation, a $10^{o}C$ rise in temperature results in a 8.3 w/m^2 increase in $LW\downarrow$. The reason for this relatively low increase in $LW\downarrow$ with temperature is not immediately apparent, but may reflect the dominance of other variables in altering LW. It could be expected that $LW\downarrow_R$, away from the influence of urban smoke effects, would show better relationship with temperature, but this is not so.

TABLE 5.6

Summary of Regression Analysis (Temperature)

Dependent Variable	No. Obs.	a	b	r	Significance
Term LW↓% urban excess	160	9.567	-0.4967	-0.10462	N.S.
Winter LW↓% urban excess	50	11.117	-1.0134	-0.20381	N.S.
Winter LW↓ urban	50	320.547	1.034	0.32694	0.02
Winter LW↓ rural	50	260.69	1.091	0.1984	N.S.

The lack of a relationship between LW$\downarrow$ urban excess and urban excess temperatures is unexpected. However, as shown in Table 5.3, the diurnal variation of LW$\downarrow$ is considerable, perhaps because of the strong diurnal cycle of smoke levels so that the lag effects between heating and cooling of the urban site relative to the rural may be masking any relationship between temperature and LW$\downarrow$. The only way to test this would be to analyse data for a given time of day, for example midnight, but not enough data was available to do this in this study.

The reason for the urban temperature lag has been attributed to greater thermal admittances in city surfaces. A further possible reason for the rural excess temperature not discussed previously would be the greater SW$\downarrow$ energy incident upon rural surfaces compared to urban surfaces. However, it appears that much of this energy is regained at the surface in urban areas by the increased LW$\downarrow$ as total incoming energy is similar for both urban and rural sites. Even given this replacement of SW$\downarrow$ by LW$\downarrow$, it follows that such an exchange of energy would mean a lag in heating at the surface which could give rise to the situation described in Table 5.3. This lag would tend to accentuate urban temperatures at night.

Vapour Pressure

Atmospheric vapour pressure is another variable which according to theory should have a strong influence on LW$\downarrow$. Table 5.7 is a summary of regression analysis for these two variables. Urban excess LW$\downarrow$ for both the full term of the study and for the winter period shows no relationship with urban excess vapour pressure. This is to be expected in consideration of measured urban/rural differences in vapour pressure which were always small in magnitude. In terms of explanation of urban/rural differences in LW$\downarrow$, vapour pressure appears to play a very minor role compared with other possible factors. Vapour pressure was also examined with respect to its possible effect on LW$\downarrow$ at point locations.

TABLE 5.7

Summary of Regression Analysis (Vapour Pressure)

Dependent Variable	No. Obs.	a	b	r	Significance
Term LW↓% urban excess	160	10.485	-0.01240	-0.02143	N.S.
Winter LW↓% urban excess	50	10.144	0.001256	0.001695	N.S.
Winter LW↓ urban	50	306.758	4.165	0.2055	N.S.
Winter LW↓ rural	50	233.404	4.3059	0.1712	N.S.

For the individual sites, the correlations were slightly greater but were still not significant.

Wind Speed and Direction

The variables of wind speed and direction are important indirectly in radiation climatology, as they determine dispersal and the direction of movement of pollutants.

Table 5.8 shows a summary of correlation analysis performed on wind speed. Correlation between measured wind speed and urban LW$\downarrow$ excess is significant at the 0.01 level for both full term and winter data. The relationship is a negative one as would be expected with a variable efficient in dispersal of pollution.

Winter data shows a lower y intercept than data for the full term. The reason for this is uncertain, but may be due to a differing effect of wind on pollutants winter and summer. Winter type pollution, being trapped relatively low to the ground, is more strongly influenced by wind than summer type pollution. The a coefficient suggests an urban LW$\downarrow$ excess of 14.2% for winter data at zero wind speed and the inclusion of data from other seasons lowers this by 2%.

A consideration of the effect of wind speed on LW$\downarrow$ at the individual sites reveals little relationship. This is not surprising in view of the results of the relationship between smoke and LW$\downarrow$ at point locations.

While wind speed appears to be strongly related to urban LW$\downarrow$ excess, wind direction theoretically should also be important. Given that surface and lower atmospheric temperatures are higher in general in urban areas than over the countryside surrounding the city, it follows that the movement of air from the city across the colder surface air of the rural areas would result in higher radiating temperatures above than predicted by surface temperatures at a rural site.

This hypothesis is tested using winds from two directions at the rural site, one direction drawing air from across the city, and the other drawing rural air across the site. The behaviour of the LW$\downarrow$ component at the

TABLE 5.8

Summary of Regression Analysis (Wind Speed)

Dependent Variable	No. Obs.	a	b	r	Significance
Term LW↓% urban increase	160	12.314	-0.5121	-0.3316	0.01
Winter LW↓% urban increase	50	14.206	-1.020	-0.4221	0.01
Winter LW↓ urban	50	281.689	0.26135	0.0524	N. S.
Winter LW↓ rural	50	221.384	0.1013	0.00428	N. S.

rural site is considered, along with the deviation of the measured LW↓ from the predicted for the two wind directions on 11 and 12 June (Table 5.9). On each of these days a typical sea breeze sprang up from the east in the early afternoon after calm mornings with light downslope katabatic winds.

While the observed LW↓ flux in Table 5.9 does not appear to show any obvious fluctuation with wind direction, the deviation of predicted LW↓ from observed LW↓ does appear to show a relationship with wind direction. The Brunt equation (5.4) is shown in a following section to work reasonably well for prediction of LW↓ for a rural site. On the basis of observed surface temperatures and vapour pressures, the observed LW↓ under the easterlies becomes considerably larger than predicted. The reasons for these trends appear to be the higher temperature and atmospheric emissivity of the air advected from over the city under the easterly. One other possible reason could be the development and destruction of strong low level inversions at this site in the morning, followed by the reformation of the inversion in the late afternoon. This would have the effect of having warmer air radiating from above at times of maximum inversion. From the evidence available in this study it is not possible to decide the most likely reason for the observed deviations of LW↓ from the predicted.

It therefore appears possible that wind direction, as well as wind speed, is an important determinant of the distribution of LW↓ across the Christchurch urban/rural area. Wind direction would be particularly important at the rural site where it could determine whether overhead atmospheric constituents of pollutants and temperature have an urban or rural origin. The true influence of wind direction on LW↓ cannot be determined from the short analysis here.

Atmospheric Mixing Depth

It would be expected that atmospheric mixing depth, being a predictor of pollution concentration in the surface boundary layer, would correlate

TABLE 5.9

Influence of Wind Direction on LW↓ at Rural Site

11 June

Time	Observed	Predicted	Difference	Wind Direction
00-02	244.8	233.3	4.9	Calm
4	248.3	234.9	5.7	West
6	265.9	239.1	11.2	Calm
8	249.4	248.3	0.4	S. West
10	230.3	244.6	-6.2	North
10-12	244.9	253.8	-3.6	Calm
			$\overline{X}$ 2.07	
14	252.2	249.6	1.0	East
16	292.0	255.9	14.1	East
18	255.6	235.2	8.8	East
20	244.3	226.6	7.8	Calm
22	243.5	213.6	14.0	East
24	244.6	216.1	13.2	Calm
			$\overline{X}$ 9.8	
12 June				
00-02	242.2	222.3	8.9	S. West
4	242.3	223.3	8.5	Calm
6	244.8	224.3	9.1	S. West
8	236.7	219.3	7.9	Calm
10	246.6	241.7	2.0	Calm
10-12	240.5	258.2	-7.3	Calm
			$\overline{X}$ 4.85	
14	255.6	253.8	0.7	East
16	238.3	220.3	8.2	East
18	260.7	230.9	12.9	East
20	258.3	230.5	12.1	East
22	261.1	230.4	13.3	N. East
24	244.4	211.2	15.1	S. West
			$\overline{X}$ 10.5	

well with any urban LW↓ excess. A correlation between 160 observations of LW↓ excess and daily mixing depth failed to show any significant relationship r = -0.09578). The relationship was a negative one as would be expected. The major problem lies in the application of one daily mixing depth to hourly LW↓ urban excesses which are quite variable during the day. It is not feasible to alter the mixing depth by including hourly surface temperatures, as this would imply the assumption of a static vertical atmospheric temperature profile, an unlikely event.

<u>The Relative Importance of Variables in the Determination of Urban/Rural LW↓ Differences</u>

Interrelationships between four independent variables and the one dependent variable were considered in a multiple correlation carried out on 50 hourly winter observations. The analysis yielded the correlation matrix outlined in Table 5. 10(a) where the coefficient of multiple correlation was 0. 6254. An F-test showed the relationship to be significant at the 0. 01 level.

An application of partial correlations to individuals to test for intercorrelations between independent variables suggested the order for entering variables into the multiple regression equation in order to obtain best explanation of variance.

Table 10. 5(b) shows each independent variable's contribution to the variance in urban LW↓ excess. The dominant influence of smoke is easily detected, explaining 27. 2% of variance with the other variables combined adding only another 11. 9%. The surprising factor is the strong showing of temperature, in spite of the negative relationship which is contrary to what is expected. As suggested earlier, this anomalous relationship may result from lag effects operating in the heating and cooling of the urban and rural sites. Wind speed also is surprising in that it explains the least variance of any of the variables. This is because of its very strong correlation with smoke which is dominant in the determination of LW urban/rural %.

TABLE 5.10

(a) Variables Influencing Correlation Matrix Urban/Rural LW↓ % Increase.

Log smoke	Urban temperature excess	Wind speed	Urban excess vapour pressure	Urban LW↓ % excess	
1	0.166	-0.550	0.162	0.522	Log smoke urban excess
	1.0	0.139	0.647	-0.203	Urban temp. excess
		1.0	0.195	-0.422	Wind speed
			1.0	0.001	Urban excess vapour pressure
				1.0	Urban LW↓ % excess

(b) Independent Variables' Contribution to % Urban Increase in LW↓

Independent Variable	Total Explained Variable	Variable explained by new variable	F Ratio	Significance
Urban excess log smoke	27.2	27.2	17.24	0.001
Urban excess temperature	35.96	8.76	12.63	0.001
Urban excess vapour pressure	37.78	1.82	8.91	0.001
Wind speed	39.11	1.33	6.90	0.001

It therefore appears that urban smoke plays as dominant a role in modifying urban/rural differences in LW$\downarrow$ as it does in modifying SW$\downarrow$; this in no way disguises the fact that the two are very closely related. The true effect of temperature may be being disguised by the lag effect of the urban temperature, and this has prompted a multiple regression for the urban site alone which resulted in the correlation matrix shown in Table 5.11.

The explanation of variance given by all these variables was only 13.27% and an F-test showed the relationship to be not significant. Application of partial correlations to the independent variables suggested that temperature be entered first into the equation for maximum explanation of variance, followed by wind speed, smoke and vapour pressure. Temperature at this site explained 10.6% of the variance in $LW{\downarrow}_U$ by itself, with the other variables only contributing 2.7% more.

This analysis therefore shows that while temperature is the most important determinant of LW$\downarrow$ over time at one place, urban/rural variations in smoke appear dominant in the spatial pattern of LW$\downarrow$ across the city. All other variables have little impact beside these two major variables.

PREDICTION OF LW$\downarrow$ IN URBAN ATMOSPHERES

Many different theoretical approaches to prediction of LW$\downarrow$ have been developed, especially in relation to the effect of aerosols. The work of Atwater (1971) and Outcalt (1972) is typical of such approaches. However, most of these models require as inputs information not available in this study. Consequently the analysis of mechanisms affecting LW$\downarrow$ is restricted to rather simplified determinations of equation 5.1.

These are simple formulae relating commonly measured meteorological parameters such as temperature, vapour pressure and humidity, to the effective atmospheric radiation. They include formulae proposed by Brunt (1932), Idso and Jackson (1969) and Swinbank (1963), and all

TABLE 5.11

Correlation Matrix

Variables Influencing $LW\downarrow_U$

Log Smoke	Temperature	Vapour Pressure	Wind speed	$LW\downarrow_U$	
1.0	-0.130	0.78	-0.55	0.001	Log smoke
	1.0	0.654	0.271	0.326	Temperature
		1.0	0.350	0.205	Vapour pressure
			1.0	-0.052	Wind speed
				1.0	$LW\downarrow_U$

se some derivation of the Stefan Boltzmann relation (equation 5. 1). The Brunt equation follows the Stefan Boltzmann relation closely, where;

$$LW\downarrow = \acute{\epsilon}\sigma T^4 (a + b\sqrt{e}) \qquad .... (5.4)$$

where a and b are constants and e is vapour pressure in mb.

The bracketed term in the equation is the empirically derived relationship predicting atmospheric emissivity, or radiating efficiency (Le Drew, 1975).

The limitation of all prediction models for atmosphere radiation lies in the specification of the effective emissivity, $\acute{\epsilon}$, which is dependent on temperature and water vapour conditions in the lower atmosphere. It can be appreciated that screen observations of temperature and vapour pressure do not always approximate the average for the portion of the atmosphere which emits $LW\downarrow$. However, Kondratyev (1969) showed that 99% of total atmospheric radiation inside the atmospheric window originates within a shallow layer 4 km thick.

The predictor equations have proven quite accurate under natural conditions at sea level, but under certain conditions they have shown a certain amount of deviation from observed values. Le Drew (1975) examined the formulae listed above for their accuracy in predicting atmospheric emittance at high altitudes, and found limitations in their applicability to those particular regions. Problems with the equation suggested that reasons for deviations from observed values of radiation lay in the emissivity predictor terms, and adjustments were made in the constants. It follows that the application of such equations to the non-natural urban environment could also outline possible areas for examination for differences in $LW\downarrow$ between urban and rural (natural) environments.

The Brunt equation was applied using temperature and water vapour data for the two sites for 26 June (Table 5. 12) using constants $a = 0.605$ and $b = 0.048$, derived by Sellers (1972). Prediction of $LW\downarrow$ at the

TABLE 5.12

Deviation of Observed from Predicted LW↓

26 June

Hr	Urban			Rural		
	Observed	Predicted	% Diff.	Observed	Predicted	% Diff.
00-02	306.3	225.6	35.4	248.2	232.4	6.8
4	305.7	221.0	38.0	263.7	234.5	12.3
6	311.5	221.0	40.7	243.5	220.4	10.4
8	298.8	215.2	38.6	229.5	210.7	9.0
10	271.2	233.3	16.3	198.2	231.3	-15.5
10-12	272.3	254.9	7.1	200.0	248.3	-10.1
14	281.8	360.3	8.1	224.7	258.2	-13.2
16	258.4	252.7	2.4	265.2	251.4	5.5
18	274.9	238.3	15.1	252.3	240.8	5.0
20	281.4	234.9	20.1	250.5	237.0	5.4
22	287.8	244.5	17.6	246.5	227.8	8.4
22-24	291.3	248.4	17.2	244.8	220.5	10.9
		underestimate	21.4		underestimate	2.9

	% Difference between Urban and Rural Observed	% Difference between Urban and Rural Predicted
00-02	23.0	-3.0
4	15.9	-5.8
6	27.9	0.3
8	30.1	2.1
10	39.1	0.8
10-12	36.0	2.6
14	25.4	0.8
16	0.0	0.5
18	7.0	-1.0
20	12.4	-0.9
22	16.7	7.3
22-24	19.3	12.6
	$\bar{X}$ 20.2	$\bar{X}$ 1.36

natural (rural) site is excellent (2.9% deviation from the observed over the day), while predictions for the urban site underestimate by a daily 21.4% average. The urban underestimation is greatest in the morning and early evening, both times of maximum pollution concentration in the urban area. A similar analysis of summer day (25 February) showed the predicted underestimation to be 10.4%, considerably less than the above, but still indicating higher urban emissivity. The Brunt equation therefore required larger a and b constants in the atmospheric emissivity term in order to successfully predict LW$\downarrow$ for the Christchurch urban site, and these constants should be varied seasonally.

A consideration of the empirical equations indicates two possible properties of the urban atmosphere which can account for both the deviation of LW$\downarrow$ measured from that predicted, and also the measured urban/rural difference, given that surface observations of water vapour and temperature at both sites explain little (accounting for a 1.4% urban excess compared to a measured 20.2% excess). Either the urban atmosphere has a higher emissivity than does the rural atmosphere at altitude, or the vertical temperature structure of the city is such that higher radiating temperatures than at the surface are boosting LW$\downarrow$. Higher emissivities in the urban atmosphere could be possibly due to a factor included in the Brunt equation, water vapour, or could be due to other constituents such as particulates not included in the Brunt equation. The two hypotheses stated above are examined below.

Moller (1951) has shown that variations in vertical temperature gradient are capable of producing marked differences in surface LW$\downarrow$ from clear skies. From available evidence it appears that this is not the reason for an urban LW$\downarrow$ excess in the Christchurch urban area. It was not possible to examine the temperatures of the atmosphere above Christchurch in this study, but it seems likely from other studies that the vertical air temperature structure over the city would tend to inhibit LW$\downarrow$ rather than promote it in comparison with LW$\downarrow$ predicted from surface characteristics.

Observations by Davidson (1967) and Bornstein (1968) over New York city and Clark (1969) over Cincinnati, have characteristically shown ground based inversions of temperature over surrounding rural areas, with either an adiabatic or weak lapse profile from the surface over the city. These studies also often found a temperature "cross-over" at about 400 metres, where temperatures above the city became cooler than over rural areas. Bornstein (1968) and Clark (1969) both found evidence of weak elevated inversions of fairly long duration over urban areas, and while they did not have sufficient temperature increase to markedly affect LW$\downarrow$, they were found by Davidson (1967) to have an important influence on pollution concentration. Rouse et al. (1973) found that temperatures at 150 metres and 2500 metres, chosen for their good indication of sky radiant temperatures, were similar above both urban and rural sites in his study.

In the present study, the presence of inversions over the rural site was recorded, but this was not possible over the city. Visual observation of pollutant cut-off suggested that an inversion was present over the city in favourable conditions,(Plate 3.2) but Ryan's kytoon study (Chapter 3) suggests that the inversion would be weaker than at the rural site. Therefore observations of the deviation of observed LW$\downarrow$ from predicted at the urban site as compared with the rural site suggest that warmer temperatures aloft are not a likely source of LW$\downarrow$ increase. From the above discussion it seems likely that sky radiative temperatures above urban areas would give similar or lower LW$\downarrow$ values than predicted from surface temperature, with the opposite occurring for rural areas, where the presence of strong inversions with higher radiating temperatures aloft would underestimate LW$\downarrow$ (note the slight rural underestimate in LW$\downarrow$ for the rural site in Table.5.5).

Therefore, by the elimination of the first hypothesis, attention is turned to the possibility of higher emissivity over the urban area causing the LW↓ excess. The higher emissivity could be due to the addition of pollutants or water vapour to the urban atmosphere. Vertical water vapour profiles above the city are unlikely to have an important effect on LW↓ excess. Little work has been done on this subject, but it is likely to show little deviation from temperature profiles which show little urban/rural differences above 300 to 400 metres. The close relationship of water vapour to temperature in vertical profile is assumed in many equations for the prediction of LW↓ (Idso and Jackson, 1969; Swinbank, 1963). Surface observations of atmospheric water vapour content show that the city has an excess atmospheric water vapour content only at night, and then usually <0.5 mb. This small amount is not sufficient to produce differences in urban/rural LW radiation that were observed in this study, and variations aloft are likely to be in the same order and magnitude or less, given the smaller urban/rural temperature differences at altitude. Oke and Fuggle (1972) have shown that a 10 mb urban/rural vapour pressure difference is required to produce a 20 w/m^2 difference in LW↓. This requirement was not ever approached over the period of this study.

The addition of pollutants to the urban atmosphere is often thought to be a cause of increased atmospheric emissivity, and this is one area where urban and rural atmospheres in this study are markedly different. Monteith (1961), Lettau and Lettau (1969), Atwater (1971) and Idso (1974) have all argued that particulates in the atmosphere will cause an increase in LW↓. Atwater (1971) developed a numerical radiation model to examine the effects of pollutants on the radiation balance. He predicted the scattering and absorption of both SW↓ and LW radiation (from the surface below and atmosphere above), and a subsequent emission of LW radiation. At night, in the absence of SW↓, there would be a marked cooling of the polluted layer with an associated decrease in LW emittance. His explanation closely followed the theoretical consideration of Lettau and Lettau (1969).

On the basis of this discussion and in consideration of regression analysis performed, it is possible to formulate a hypothesis for the urban LW↓ excess recorded in Christchurch. This hypothesis largely follows that of Rouse et al. (1973) except for the nighttime situation.

Part of the SW↓ entering the polluted urban atmosphere is reflected off the polluted layer, most is transmitted as direct or scattered diffuse beam radiation and a further part of the SW↓ is absorbed. For the Christchurch urban area, the attenuation of SW↓ under clear skies amounts to an average 14.9%, an unknown proportion being reflected and absorbed. Absorbed SW↓ energy is converted to LW radiation and is emitted both upward and downward, the downward component being the source of the increased LW↓. In this study, the daytime increase in urban LW↓ appears to balance the deficit of SW↓. Therefore there must be an extra source of atmospheric energy. Rouse et al. (1973) ascribe this extra source of energy to an increased absorption of LW↑ from the warmer city surfaces by particulates, with subsequent counter-radiation. The LW↑ from urban surfaces has long been known to be greater than from rural surfaces (Bach and Patterson, 1969; Landsberg and Maisel, 1972) and is known to peak at around solar noon when surface temperatures are highest (Sanderson, 1974). This, associated with the fact that maximum incidence and absorption of SW↓ occurs near solar noon is the reason for urban excess LW↓ to peak at about this time. This peak appears to be slightly offset to the morning because of the occurrence of the pollution peak at this time.

The continued presence of pollutants at night, and hence higher atmospheric emissivity is responsible for the continuation of LW↓ excess into the night. However, the cooling of the pollutant layer at night, in the absence of SW↓ would gradually lessen the flux of LW↓, though this trend is not consistently shown for the data shown here (Tables 5.2 and 5.3). One further possible reason for the continuation of an urban LW↓ excess at night, is the output of sensible heat from general urban warmth, heating and industry, into the lower atmospheric pollution layer with subsequent absorption and counter-radiation. In this respect the increased LW$\downarrow$ at night may be indirectly due to the urban "heat island" operating through pollution to give the measured results, a result of, and not a cause of the urban heat island.

The fact that attenuation of SW$\downarrow$, and increases in LW$\downarrow$ peak towards the daytime period of highest incident radiation and pollution occurrence indicates the importance of absorption in the process described. There are numerous solids and gases which will cause this, particularly smoke, sulphur dioxide, iron oxides, carbon dioxide, carbon monoxide, nitrogen dioxide and water vapour (Rouse and McCutcheon, 1972).

This hypothesis appears to fit and account for the observed trends and results or regression analysis of this study. The complete testing of the hypothesis awaits a much more specialised study than is possible here.

CONCLUSIONS

An examination of urban/rural variations in LW$\downarrow$ over the Christchurch metropolitan area has given the following major points:

1) Differences in LW$\downarrow$ between the urban and rural sites in this study were found to be statistically significant for clear days and not significant for other weather types. The average urban excess in LW$\downarrow$ was 8.5% for clear days over the study period.

2) The urban excess LW$\downarrow$ was found to have a seasonal trend, with greater amounts in the winter time. It is believed that this trend is due to the presence of particulates in the urban atmosphere. A daily trend in urban excess LW$\downarrow$ was also found and also closely followed pollution trends.

3) The excess LW$\downarrow$ at the urban site almost exactly balanced the SW$\downarrow$ loss; therefore daytime total energy income at both sites was found to be in balance. At night, the urban site exhibited a net excess in

incoming radiation, due to the continuation of the LW$\downarrow$ excess into the night.

4) Regression analysis indicated that smoke pollution is the dominant influence on urban/rural differences in LW$\downarrow$, but that in terms of explaining differences at individual sites, temperature is the most important variable.

5) Deviations of observed LW$\downarrow$ from predicted LW$\downarrow$ have indicated a possible hypothesis which will explain urban LW$\downarrow$ excess in terms of absorption and reradiation of energy by a pollutant layer over the urban area.

CHAPTER SIX

SPATIAL VARIATIONS OF SW↓ AND LW↓ ACROSS CHRISTCHURCH

INTRODUCTION

The aim of this chapter is to confirm the absolute urban/rural trends already identified and to outline the spatial patterns of these radiation parameters which are not obvious from the fixed climate stations. Initially, there is a short discussion of the trends in incoming radiation between the two major sites as determined by single directional traverses. A comparison between traverse and fixed site data should help establish the validity of using traverses to expand the data base. This is followed by an examination of the city-wide pattern of incoming radiation with particular respect to possible variables which can affect LW↓ and SW↓. The analysis is mainly descriptive and attempts to determine if the relationships found to hold for the fixed stations hold as well for the traverse data.

SINGLE DIRECTIONAL TRAVERSES

Daytime Variations in Tr and LW↓ Between Major Sites

Of eleven traverses completed between the two major sites over the study period, three were discarded because of instrumental failure or cloud problems. Table 6.1 shows the data for the remaining traverses over each of the seven sites used. The sites are shown in Figure 2.1 and detailed in Appendix I. A general urban/rural trend toward higher transmissivities can be perceived for all traverses, though the urban/rural differences are quite variable from day to day over the study period. A seasonal trend towards higher winter transmissivities for all sites can be noted. This trend was also noted for the major stations and was attributed to seasonal variations in water vapour.

TABLE 6.1

Traverse Transmissivities Between Major Sites.

Date		18.3	19.3	7.4	22.4	21.5	11.6	12.6	26.6	$\overline{X}$
Rural Site	(1)	0.7881	0.7771	0.7169	0.8131	0.8010	0.8749	0.8457	0.8083	0.8031
	(2)	0.789	0.7700	0.6940	0.7471	0.7914	0.8337	0.8217	0.8079	0.7807
	(3)	0.7629	0.7609	0.6885	0.7178	0.7792	0.8304	0.8082	0.7932	0.7676
	(4)	0.7708	0.7571	0.6890	0.7120	0.7884	0.8118	0.8000	0.7855	0.7642
	(5)	0.7458	0.7495	0.6905	0.7045	0.7858	0.7976	0.8074	0.7754	0.7570
	(6)	0.7644	0.7354	0.6883	0.6895	0.7602	0.7993	0.7926	0.7461	0.7469
Urban Site	(7)	0.7396	0.7531	0.7068	0.6911	0.7818	0.8240	0.7830	0.7660	0.7556
Tr urban/rural % decrease (maximum)		6.5 (5.48)	5.7 (3.4)	4.1 (3.6)	17.9 (10.25)	5.4 (4.8)	9.7 (5.68)	8.0 (7.2)	8.4 (10.95)	7.5
Urban Site Pollution at that hour		0.0	6.0	8.0	100.0	30.0	150.0	100.0	106.0	
Wint Direction at airport and speed kts.		E 14	E 12	NE 11	N 3	SW 8	NE 3	NE 6	Calm	

For all data the Tr urban/rural % is the maximum difference observed on the traverse. This was usually at traverse site 1 (near airport), and traverse site 6 (near the centre of the city). The consistently low Tr readings at site 6 (between the city centre and the major urban site), indicate the degree of atmospheric turbidity in the area. An examination of view factors suggests that these are unlikely to be the reason as sites 4, 5 and 7 all have lower view factors yet higher transmissivities than site 6.

A comparison of Tr urban/rural % for the traverse and fixed sites at the same time in Table 6.1 (fixed site bracketed), show very similar amounts of attenuation. Of more importance than absolute differences between fixed site and traverse data, is the good agreement between them for day to day trends. Initial comparison of trends reveal a certain relationship with smoke levels, an observation that was made for fixed site data also. Attenuation revealed in the late summer traverses in the absence of smoke, indicates the presence of some other agent of attenuation. The importance of wind speed in determining smoke and Tr variation is also revealed in Table 6.1.

View factors appear to have little effect on Tr values, this being substantiated by a comparison of average Tr values from site 3 and 4 which have view factors of 90.5 and 75 respectively. The average difference in Tr for these sites was only 0.4%.

Table 6.2 shows LW↓ for each site on the same traverses. While there are problems in the computation of LW↓ during daytime (Chapter 5), there appears to be a definite urban/rural trend with a term average of 9.4% urban excess at around solar noon. The average urban excess for the two hour period around T.S.N. at the two fixed sites was not significantly different at 10.5%. The highest LW↓ urban/rural % measured was 22.96 on a day of high pollution concentration at the time of the traverse.

TABLE 6.2

Traverse Daytime LW↓ Between Major Sites (w/m^2)

Date		18.3	19.3	7.4	22.4	21.5	11.6	12.6	26.6	$\overline{X}$
Rural Site	(1)	303.26	324.2	328.87	260.81	289.67	210.76	255.22	281.02	281.73
	(2)	308.32	329.27	340.91	259.34	289.92	215.83	275.87	274.3	286.72
	(3)	314.45	328.18	337.52	280.1	301.74	225.79	274.6	280.5	292.86
	(4)	325.42	342.14	352.8	293.15	300.73	238.42	284.7	275.7	301.63
	(5)	342.31	351.26	338.78	303.36	298.58	247.53	284.1	277.94	305.48
	(6)	336.65	350.32	342.24	294.48	306.32	256.26	274.2	302.43	307.99
Urban Site	(7)	343.2	352.1	311.6	306.63	302.19	259.16	298.41	292.06	308.17
LW↓ urban/rural % (maximum difference)		13.17	8.6	6.3	17.56	4.32	22.96	16.91	10.2	9.4
Urban excess temperature °C		-2.25	-0.75	-0.95	-0.45	0.15	0.2	-0.65	1.15	
Urban Site Pollution		0	6	8	100	30	150	100	106	
Wind Speed and Direction		E 14	E 12	NE 11	N 3	SW 8	NE 3	NE 6	Calm	

A consideration of LW$\downarrow$ urban/rural %, smoke pollution and urban temperature excess indicates a very strong relationship between smoke andLW$\downarrow$ urban/rural %, with less relationship between urban temperature excess and LW$\downarrow$ urban/rural %. This agrees with observations made in the previous chapter. It is surprising that the effect of warm radiating surfaces at site 5 (central city), did not have a greater effect on LW$\downarrow$ at that site. It is possible that the dominant effect of SW$\downarrow$ in the equation for determination of LW$\downarrow$ is masking the trends in LW$\downarrow$ due to other variables.

Nightime Variations in LW$\downarrow$ Between Major Sites

Clear weather nightime traverses were undertaken on eight occasions and data collected is presented in Table 6.3. Three important points arise from this data. There is a general summer-winter trend in decreasing atmospheric LW$\downarrow$ due to seasonal effects as described previously in this thesis. Also evident is a marked peak in radiation at site 5 in the central city which was not obvious for day-time traverses. This is probably due to energy storage in adjacent buildings during the day and released in the cool of the evening. Finally, the LW$\downarrow$ urban/rural % difference is lower than that recorded during the day (Table 6.2). This is probably due to the daytime solar radiation effect discussed in the previous chapter.

A comparison with data obtained from Table 5.2 shows that at the same time as traverses were undertaken, urban LW$\downarrow$ percent excesses amounted to an average 5.2 for the major sites. The average urban excess of 7.7% measured by traverse agrees well, considering that the traverses use the maximum urban/rural differences.

It appears from Table 6.3 that the urban excess LW$\downarrow$ as recorded by the major radiation stations is an underestimate, as the England Street traverse site (7) consistently records the lowest LW$\downarrow$ of the four urban sites. However, the view factors at sites 4 and 5 may have an important bearing on this.

TABLE 6.3

Traverse Nightime LW↓ Between Major Sites (w/m^2)

Date		19.3	25.3	21.4	7.5	26.6	7.6	26.6	29.6	$\overline{X}$
Rural Site	(1)	285.52	282.7	261.1	261.22	265.9	234.1	234.11	270.8	261.93
	(2)	295.68	287.58	261.65	262.62	277.1	242.5	240.18	266.35	266.71
	(3)	293.85	288.78	260.37	260.24	277.75	252.81	264.0	267.7	270.69
	(4)	302.34	296.73	268.4	278.48	285.41	258.58	258.41	268.2	277.11
	(5)	317.29	297.19	275.19	283.66	289.7	257.92	261.49	273.83	282.03
	(6)	296.69	290.56	266.25	274.69	288.3	253.6	255.23	266.79	274.01
Urban Site	(7)	293.92	288.2	266.16	273.8	292.5	254.6	253.08	264.48	273.34
LW↓ urban/rural % (maximum difference)		11.0	5.0	5.7	9.1	10.00	10.6	11.7	2.8	7.7
Urban Site Smoke		38	10	90	124	106	46	334	22	
Urban excess temperature °C		4.55	-0.5	1.35	-0.25	3.0	2.8	4.5	-1.05	
Wind Speed and Direction		NE 2	NE 8	NE 5	NE 2	E 6	NE 6	Calm	NE 14	

Trends of measured LW$\downarrow$ urban/rural % and urban smoke and temperature excess indicate that temperatures may play some part in the variation. All large urban LW$\downarrow$ excesses appear to be associated with larger temperature excesses (3^{o}C or greater). Trends with smoke levels also appear strong. Wind speed, through its effect on both pollution and the urban "heat island" is also related to urban excess LW$\downarrow$.

TWO DIRECTIONAL TRAVERSES

Data used in this section includes eight traverses, half of which were undertaken at night. Traverse data from a 1975 Honours' Climatology project is used as well as 1976 data. The dates of the traverses are given in Appendix II and the locations of the 19 sites are shown in Figure 2. 1.

Before beginning a discussion of the spatial aspects of incoming radiation it is necessary to more fully discuss the spatial pattern of likely causative variables beyond that which was possible with fixed site data. Spatial patterns of smoke pollution have already been described in Chapter 3. This discussion relates to the other theoretically important variables of temperature and vapour pressure.

Temperature

While absolute urban/rural temperature differences have been discussed in Chapter 3, this outline gave little indication of the city-wide pattern of temperature. Both Sham (1966) and Kingham (1969) have described the pattern of temperatures across the Christchurch urban area. Kingham (1969) outlined a general pattern of temperature distribution across Christchurch on calm clear nights which was closely related to topographic features and building density. He found consistently high temperatures over the central city area, towards the sea and up the Port Hills.

Despite the relatively small number of sample sites (19), average traverse nightime temperatures reveal a similar trend to that described by Kingham (Table 6.4(a)). A distinct "heat island" is revealed near the centre of the city in both north/south and east/west traverses. The north/south traverse shows the maximum average heat island intensity of 4.95^{o}C (between sites A and E). The greater variation in temperature over this traverse is probably a result of the more distinct urban/rural traverse. The east/west traverse is never effectively in true rural surroundings even at the Islington site K.

As well as cooler temperatures towards rural areas there are increases in temperature up the hills to the south of the city and towards the sea to the east (site 5). The temperature increase up the hill is due to the presence of the low level temperature inversion that becomes established over the city on cold clear nights, while the sea has the effect of causing advection of comparatively warm moist sea air over the adjacent land areas.

Table 6.4(b) shows the temperature patterns across Christchurch as measured on daytime traverses. The urban "heat island" is much less pronounced ($< 1^{o}$C) for both traverse directions and there is a cooling trend visible up the hills in response to temperature lapse with altitude. A further cooling trend during the day is seen towards the sea where onshore breezes are the agent responsible.

To assess the influence of gross land use on the heat island effect, the average maximum heat island found in this study (5.4^{o}C) was plotted along with some other New Zealand data from McBoyle (1970) on a graph of population and heat island intensity (Figure 6.1). This graph also shows the results of a similar study for North America and Europe obtained by Oke (1973). Oke attributed the lower increase in heat island intensity for similar populations in Europe to factors such as less artificial heat generation and greater surface evaporation rates because of more vegetation. Although the New Zealand data is quite limited, it seems that the heat island intensity for a given population is lower still than Europe. This can probably be related to a lower

TABLE 6.4

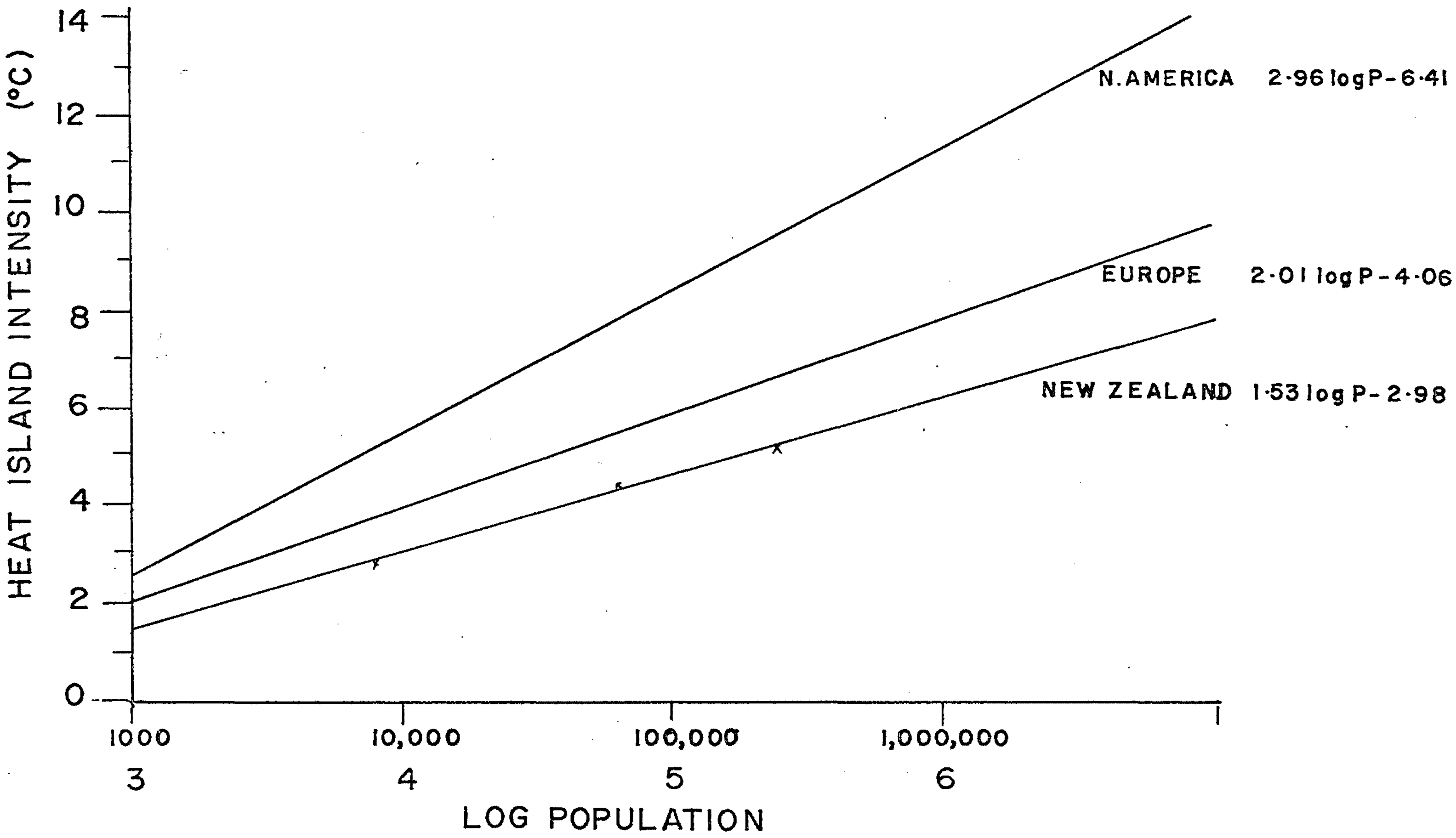
(a) Nightime Traverse Temperatures ^{o}C.

Site	North/South	Site	East/West
A) Stanleys Rd	1.69	K) Islington	3.05
B)	3.26	L)	3.76
C)	3.6	M)	4.57
D)	4.92	N)	4.94
E) Cathedral Sq	6.64	O) Railway Stn	4.71
F)	4.8	P)	4.77
G)	4.95	Q)	3.18
H)	6.87	R)	3.56
I)	6.57	S) New Brighton	5.54
J) Sign of Kiwi	5.9		

(b) Daytime Traverse Temperatures ^{o}C

Site	North/South	Site	East/West
A) Stanleys Rd	11.76	K) Islington	11.9
B)	12.39	L)	12.14
C)	11.66	M)	12.44
D)	11.94	N)	12.45
E) Cathedral Sq	12.26	O) Railway Stn	12.54
F)	12.18	P)	12.32
G)	12.1	Q)	12.65
H)	11.69	R)	11.95
I)	10.79	S) New Brighton	10.8
J) Sign of Kiwi	10.72		

Figure 6.1 Population and Heat Island Effect



N. AMERICA 2·96 log P - 6·41
EUROPE 2·01 log P - 4·06
NEW ZEALAND 1·53 log P - 2·98
HEAT ISLAND INTENSITY (°C)
14
12
10
8
6
4
2
0
1000
10,000
100,000
1,000,000
3
4
5
6
LOG POPULATION

level of artificial heat production than in both North American and European cities. New Zealand cities are also generally well vegetated and this is likely to lead to more loss of energy through evaporation and lower thermal admittances.

Vapour Pressure

Vapour pressure, because of its close relationship with temperature and topographic features, is also quite variable across the Christchurch urban/rural area. Table 6.5(a) shows the average vapour pressure by site for nightime traverses, where the similarity of vapour pressures at the Ferry Road crossover point indicates the comparability of data from both the north/south and east/west traverses.

The north/south traverse shows up particularly well the increase in vapour pressure towards the centre of the city ($>$1mb difference between sites A and E). This has been related to the trapping of moist daytime air in city canyons, and a lack of cool surfaces for dew formation. The east/west traverse does not show any particular trends, perhaps because the Islington site is not a true rural site. However, this traverse does indicate a distinct rise in vapour pressure at site S, where there is advection of warm, moist air from over the adjacent sea. Site R, less than 1.5 km inland, is an average 0.8 mb lower than the site bordering the sea. One further trend that can be noted is the decrease in vapour pressure with altitude up the Port Hills on the north/south traverse (sites, H, I and J). This trend is expected from knowledge of the distribution of water vapour in the lower atmosphere (Lowry, 1970).

Daytime traverses (Table 6.5(b)) show similar trends with respect to the effect of altitude and proximity to the sea, but, as for the major sites, the urban/rural nightime vapour pressure trends are reversed in the daytime. The east/west traverse in the daytime shows the most marked urban/rural difference with site N near the centre of the city showing a 0.9 mb deficit on the rural site at Islington. The major

TABLE 6.5

(a) Average Nightime Vapour Pressures on Traverse (mb)

Site	North/South	Site	East/West
A) Stanleys Rd	5.53	K) Islington	6.48
B)	5.83	L)	6.62
C)	6.21	M)	6.39
D)	6.13	N)	6.43
E) Cathedral Sq	6.61	O)	6.4
F) Ferry Rd	6.46	P) Ferry Rd	6.48
G)	6.26	Q)	6.24
H)	6.76	R)	6.43
I)	6.11	S) New Brighton	7.22
J) Sign of Kiwi	5.94		

(b) Average Daytime Vapour Pressures on Traverse (mb)

Site	North/South	Site	East/West
A) Stanleys Rd	7.92	K) Islington	7.39
B)	7.66	L)	7.03
C)	7.89	M)	6.82
D)	7.61	N)	6.52
E) Cathedral Sq	7.49	O)	6.77
F) Ferry Rd	7.5	P) Ferry Rd	7.25
G)	7.38	O)	7.13
H)	7.2	R)	7.56
I)	6.46	S) New Brighton	8.04
J) Sign of Kiwi	6.15		

reason for this urban deficit vapour pressure during the daytime is the lack of evaporation off nearby surfaces because of the lack of available moisture (Chandler, 1965).

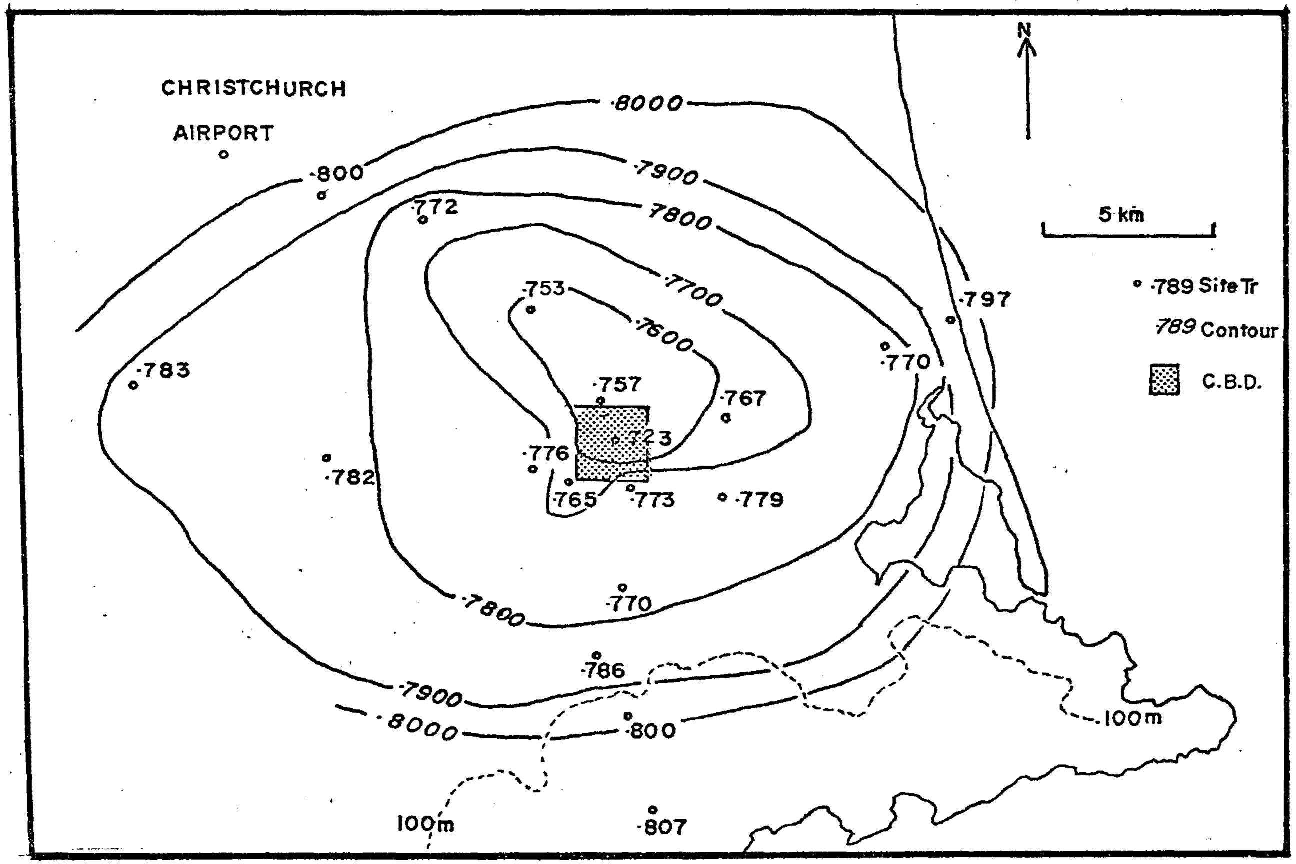
Spatial Distribution of Tr and Daytime LW↓

The spatial pattern of average Tr values for the four daytime traverses is shown in Figure 6.2. The highest average Tr recorded was .8071 at the Sign of the Kiwi (J) at an altitude of over 300 metres on the Port Hills. This was probably due to a very clear, relatively vapour free atmosphere above this site. The very low values recorded were in the central city (0.7227), and are probably a consequence of the very low view factor due to the blocking effect of high buildings and also the effect of smoke. Plate 6.1 shows traverse site E, with the buildings in the background being five stories high. This plate also illustrates other problems that the practising climatologist must endure.

From the central city transmissivities progressively increase in all directions. By the time the sea is reached in the east and the airport in the west, Tr is back up to 0.8000. Tr values also climb rapidly up the hill in response to the drop in pollution above the urban smoke layer. Application of the Brooks equation (4.4) to data from site G at the base of the Port Hills and site J 300 metres up the Hills, indicates that for a change in altitude and vapour pressure, holding all other factors constant, there should be a 0.5% increase in Tr up the hill. However, actual measured Tr increases by 6.2% over that distance and it appears that the reason for this deviation lies in the urban smoke blanket which only reaches part way up the hills.

Figure 6.3 relates measured transmissivity to the most likely factors responsible for its variation in space. The smoke data are for the nearest smoke pollution monitor and although 24 hour recordings from these stations are sometimes poorly representative of the site at time of radiation measurement, the peaks in the lines agree well with the dips in transmissivity for both directional traverses.

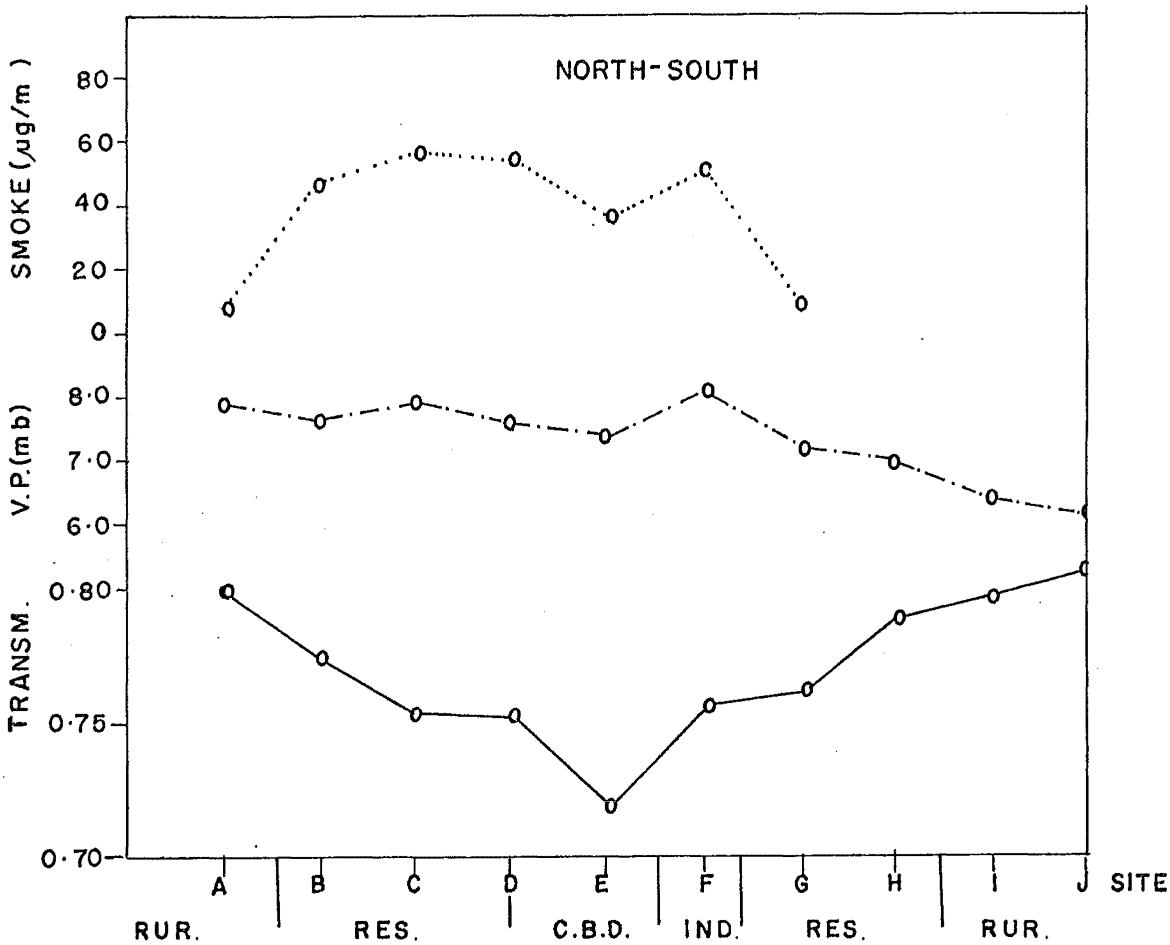
Figure 6.2 Transmissivities Across Christchurch



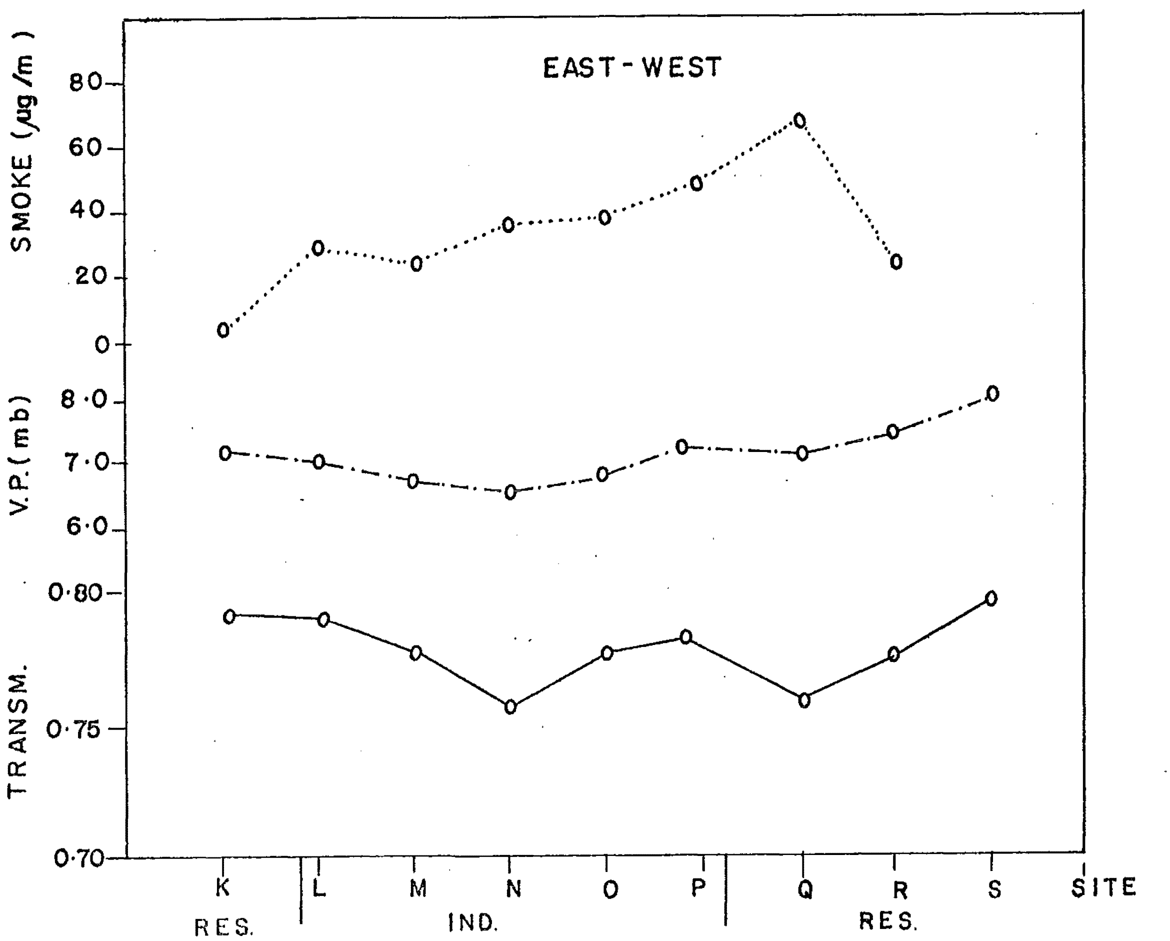
CHRISTCHURCH
AIRPORT
N
5 km
·789 Site Tr
789 Contour
C.B.D.
8000
7900
7800
7700
7600
·800
·772
·753
·757
·723
·767
·776
·765
·773
·779
·782
·783
·770
·797
·786
·807
100m

Plate 6.1 Traverse Site E (Cathedral Square)

Figure 6.3 Average Relationship Between Tr and Atmospheric Variables (North/South and East/West Traverses)



NORTH-SOUTH
SMOKE (µg/m)
80
60
40
20
0
V.P.(mb)
8·0
7·0
6·0
TRANSM.
0·80
0·75
0·70
A
B
C
D
E
F
G
H
I
J
SITE
RUR.
RES.
C.B.D.
IND.
RES.
RUR.



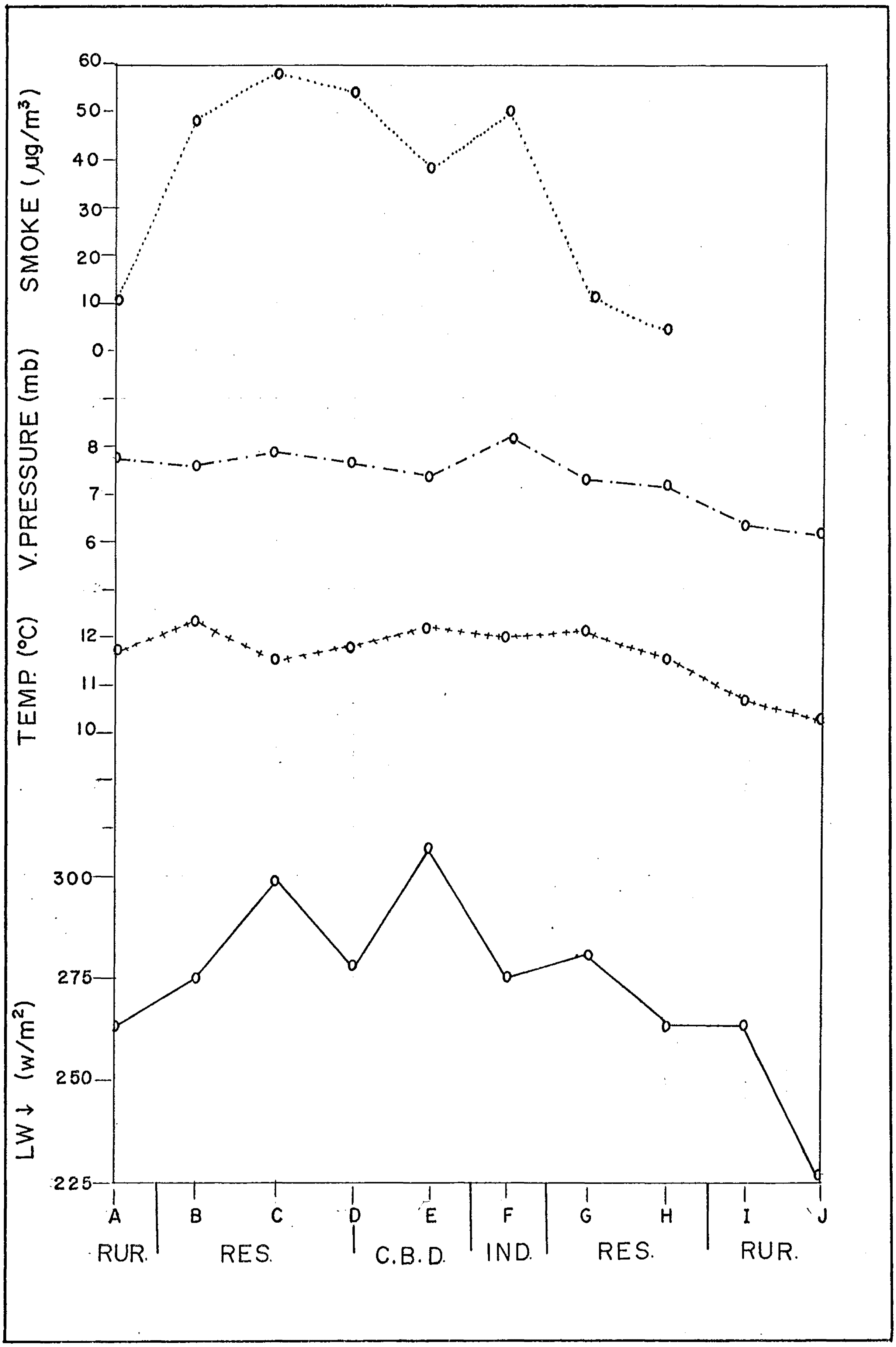
EAST-WEST
SMOKE (µg/m)
80
60
40
20
0
V.P.(mb)
8·0
7·0
6·0
TRANSM.
0·80
0·75
0·70
K
L
M
N
O
P
Q
R
S
SITE
RES.
IND.
RES.

Smoke data is not recorded near three sites on the north/south traverse, but it is certain that smoke levels drop to zero up the hill. By comparison, vapour pressure appears to explain little of the short term spatial variations of Tr and this observation supports that made earlier. That is, while vapour pressure decreases up the hills in the north/south traverse, the resultant rise in Tr is too great for vapour pressure alone to be responsible. From this brief analysis it appears that the conclusions previously made about the dominance of atmospheric pollution in determination of Tr variation through time at fixed sites, also holds true in space. The only other factor which could be more dominant is view factor, as evidenced by the Tr and smoke value at site E.

Figure 6.4 shows the LW↓ trend for north/south traverses which runs almost exactly opposite to Tr. Because of the method of computation of LW↓ during daytime, not too much significance should be attached to the trend shown. There is a notable increase in LW↓ towards the centre of the city and a decrease both up the hills to the south of the city and towards the rural area in the north. The excessively large peak at site E is due to the radiating warmth of surrounding surfaces. The spatial variation of LW↓ during daytime is clearly related to urban smoke pollution which supports the hypothesis stated in the previous chapter, that particles absorb SW↓, reducing Tr and increasing LW↓. Figure 6.4 shows that LW↓ does not appear to vary well with either temperature or vapour pressure. However the lower vapour pressure and temperature up the hill in the absence of pollution are the probable reasons for the abrupt drop in LW↓.

Because of the likely errors involved in the computation of LW↓ in daytime, especially on the mobile traverses, more detailed discussion is not warranted.

Figure 6.4 Average Relation Between LW$\downarrow$ (Daytime) and Atmospheric Variables



SMOKE (µg/m³)
60
50
40
30
20
10
0
V.PRESSURE (mb)
8
7
6
TEMP. (°C)
12
11
10
LW↓ (w/m²)
300
275
250
225
A
B
C
D
E
F
G
H
I
J
RUR.
RES.
C.B.D.
IND.
RES.
RUR.

Spatial Distribution of LW↓ at Night

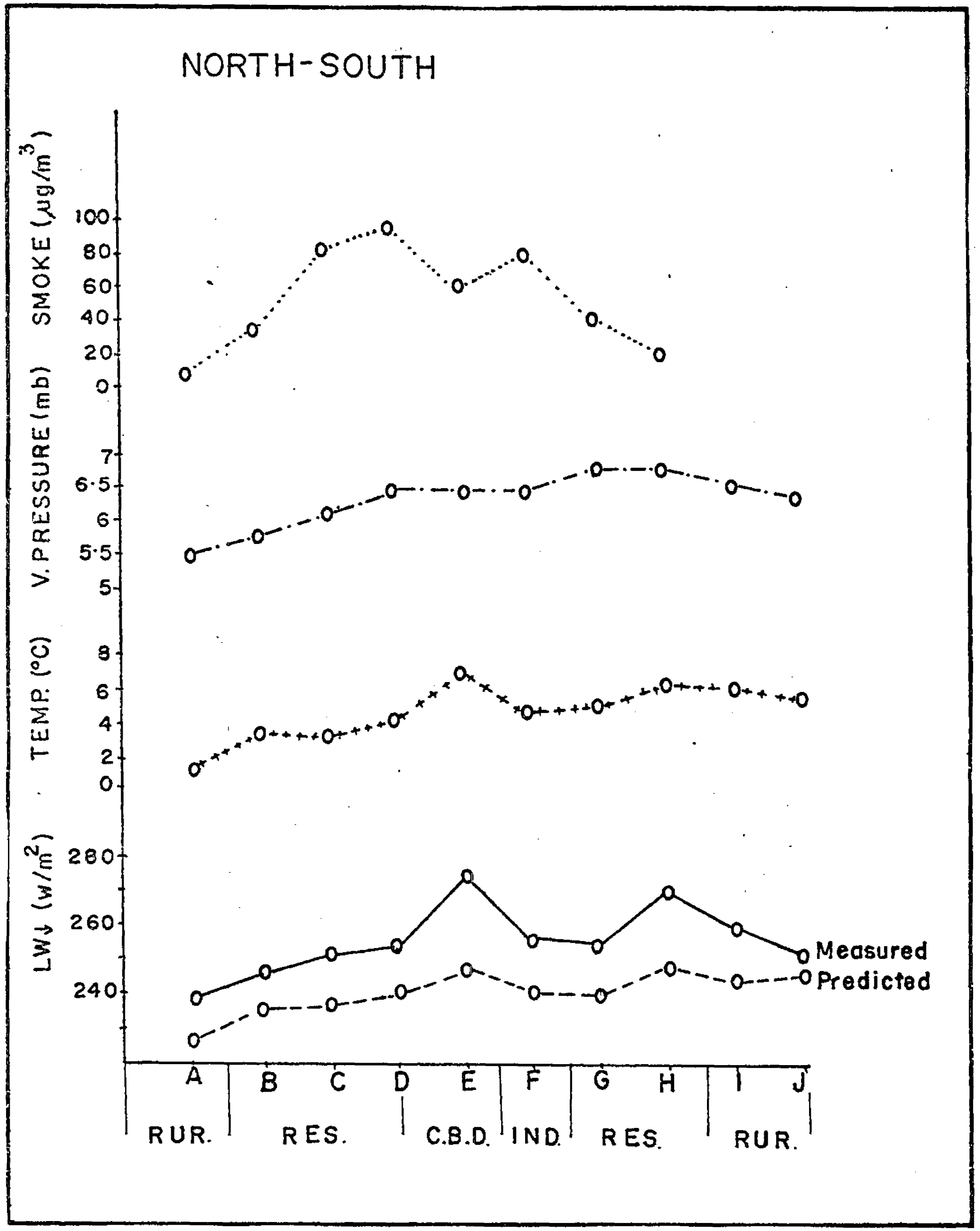
Figures 6.5 and 6.6 show nightime LW↓ trends for both the north/south and east/west traverses. Nightime LW↓ shows a similar peak in the centre of the city as daytime LW↓. The extreme peak at E on the north/south traverse can again be related to the view factor. Apart from sites D and E all other sites appear to have view factors not significantly altering LW↓ between sites. The east/west traverse shows a lower variation in LW↓ across the city than does the other traverse and the reason has been previously stated for other variables. The physical influence of the sea again causes a rise in nightime LW↓ due to water vapour and warmer temperatures increasing atmospheric emittance. Conversely, the north/south traverse reveals a decrease in LW↓ up the hill due mainly to the decrease in water vapour and to a lesser extent temperature.

A comparison of atmospheric variables possibly responsible for changes in LW↓ does not reveal any one most likely factor. In the north/south traverse pollution, vapour pressure and temperature all closely parallel the trend in LW↓. Temperature and pollution in particular peak near the central city along with LW↓. The apparent close relationship with temperature was something that was found by Oke and Fuggle (1971), but they did not monitor pollution on their traverses.

Application of the Brunt equation would, on the basis of measured temperature and vapour pressure, give similar trends in LW↓. This does appear to be the case for both north/south and east/west traverses, but a consideration of measured LW↓ and predicted LW↓ (Figure 6.7) indicates a consistently greater LW↓ towards the centre of the city than predicted, even when LW↓ at site E is disregarded. Applying the same reasoning as in the previous chapter as to the possible cause of the urban excess, it appears that the extra emissivity can only be due to the presence of pollutants.

Figure 6. 5 Nightime Average Relation Between LW↓ and Variables (East/West)

Figure 6. 6 Nightime Average Relation Between LW↓ and Variables (North/South)


NORTH-SOUTH
SMOKE (μg/m³)
V.PRESSURE (mb)
TEMP. (°C)
LW↓ (w/m²)
Measured
Predicted
A B C D E F G H I J
RUR. RES. C.B.D. IND. RES. RUR.

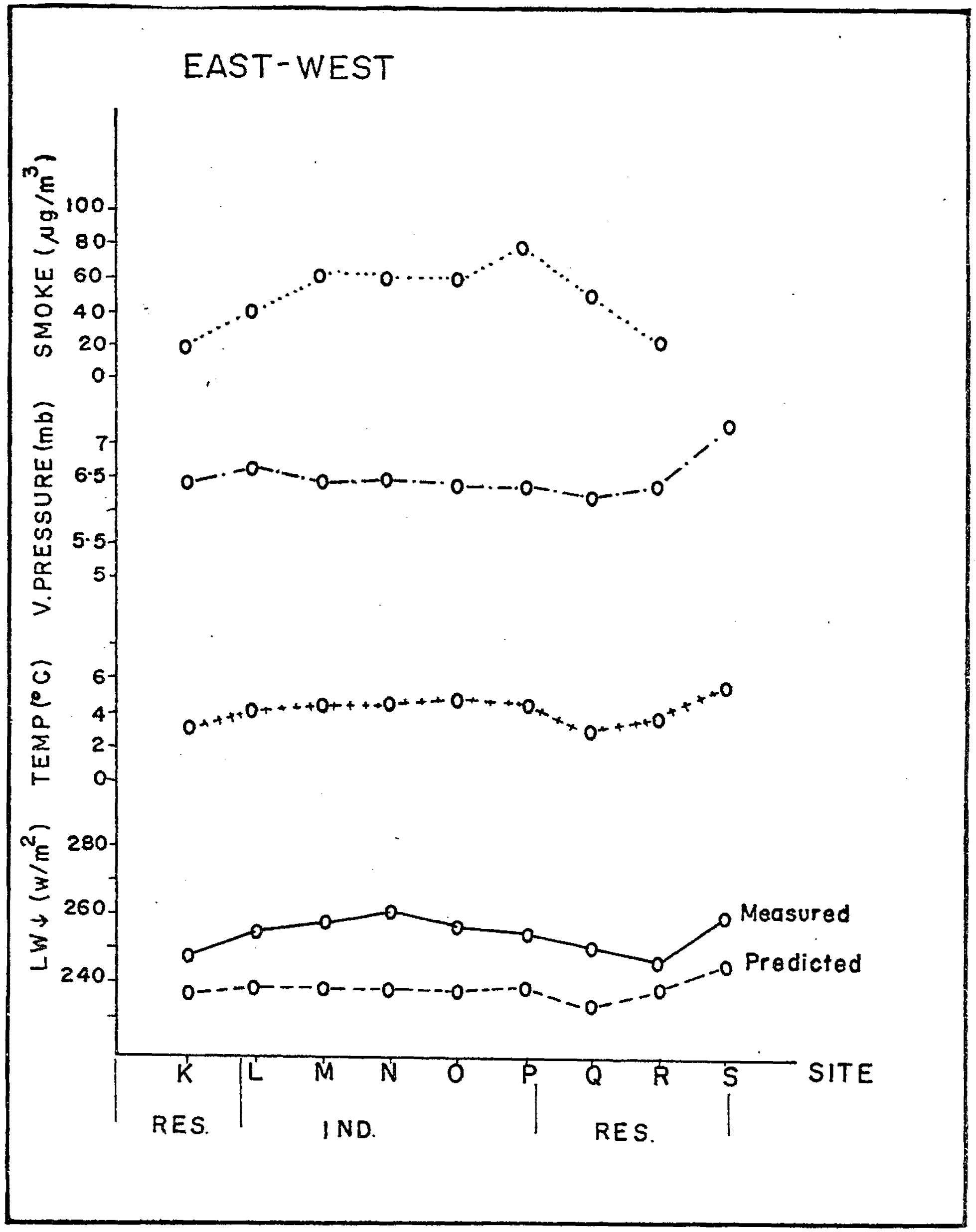
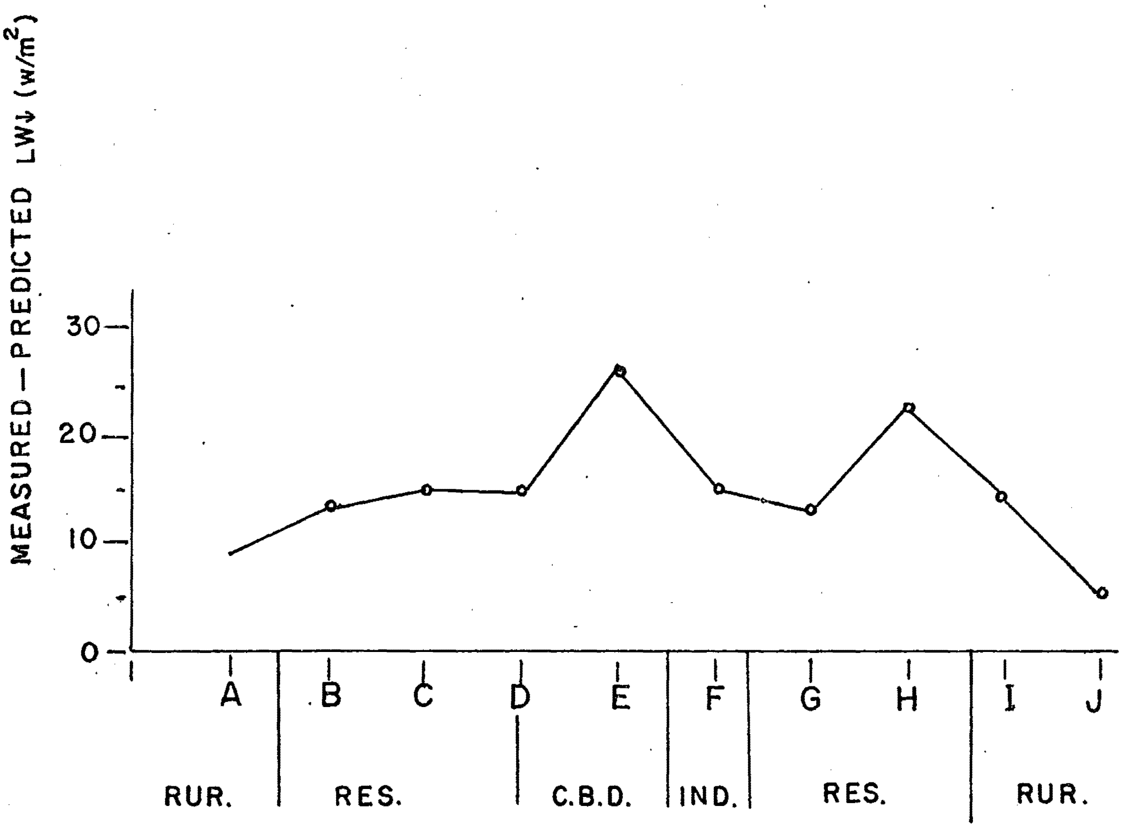

EAST-WEST
SMOKE (μg/m³)
V.PRESSURE (mb)
TEMP (°C)
LW↓ (w/m²)
Measured
Predicted
K L M N O P Q R S
SITE
RES. IND. RES.

Figure 6.7 Measured-Predicted LW$\downarrow$ (North/South Traverse)


MEASURED − PREDICTED LW↓ (w/m²)
30
20
10
0
A
B
C
D
E
F
G
H
I
J
RUR.
RES.
C.B.D.
IND.
RES.
RUR.

On the basis of results presented here it is difficult to isolate one variable most responsible for variation in LW↓ across the urban area. While the relationship of temperature and water vapour across the city explains part of the trend, it appears that urban pollution is the determinant of the final trend in LW↓ . Observations made at night as to LW↓ variation tend to support the suggestion made in the previous chapter about LW↓ urban excesses continuing into the night. Pollution and urban excess nighttime temperatures may be operating efficiently in conjunction. The output of sensible heat from general urban warmth into the lower atmospheric pollution layer is accompanied by subsequent absorption and reradiation. Therefore, the increased LW↓ at night is indirectly caused by warmer temperatures operating through the pollution layer to give the measured results. Such a hypothesis is impossible to test within the instrumental restrictions of this thesis and must only remain conjecture.

One general point that can be made with regard to both LW↓ and SW↓ is that although the spatial sampling pattern is not as detailed as desired, there does not appear to be marked changes in downward radiation with land use. This is illustrated for all traverses, and apart from some effects which have been related to view factors, the gradual transition of Tr and LW↓ values across the city suggested that a more spatially diffuse factor such as smoke or vapour pressure was causing this variation. A subsequent consideration of the variation of these factors has suggested that smoke was probably most important.

CONCLUSIONS

1) Single directional traverses between major sites gave good agreement with Tr, LW↓ (daytime) and LW↓ (nightime) urban/rural differences as measured at the major sites.

2) Two directional traverses across the urban area revealed distinct trends in radiation parameters which could be related to urban and

topographical effects. Tr showed a decrease towards the centre of the city while LW↓ (daytime) and LW↓ (nightime) showed an increase in the same direction. LW↓ was seen to increase towards the sea in response to warmer temperatures and higher vapour pressures, while LW↓ up the hills decreased largely in response to decreasing vapour pressure.

3) Apart from the view factor influence there does not appear to be marked changes in downward all wave radiation parameters with land use. It appears that there is a gradual urban/rural variation for Tr and LW↓ in response to more diffuse factors such as an urban pollution dome.

4) Tr showed a very strong relationship with measured smoke amounts across the urban area. LW↓ (daytime) also apparently showed a strong relationship with smoke but this was treated cautiously due to problems in obtaining LW↓ .

5) LW↓ (nightime) showed a general trend with all possible causative factors and simple analysis suggested that pollution was operating in conjunction with other variables, especially temperature, to produce the measured results.

CHAPTER SEVEN

CONCLUSION

SUMMARY OF CONCLUSIONS

This investigation of variation in LW↓ and SW↓ over the Christchurch area is an intial attempt at a better understanding of the urban climate of the city in terms of causal mechanisms. While a clearer knowledge of the energy balance of the urban area awaits measurement of other energy balance components, a broad aim has been to contribute to an understanding of the city's effect on the radiation microclimate. Some conclusions with regard to urban effects on the incoming radiation components have been reached.

Average attenuation of SW↓ on clear days in the central city as compared with a nearby rural site amounted to 14.9%, a high amount compared to many overseas studies. However, this may be an over-estimate because the winter high pollution season was over-represented in the period of study. Many other studies (Emslie, 1964; Probald, 1972; Yamashita, 1970) are over the whole year, or include data from all weather types. Individual daily attenuation of up to 30% appears to be similar to that of other mid-latitude cities (Rouse and McCutcheon, 1971; Sanderson, 1972). A distinct yearly and daily trend was evident towards higher SW↓ attenuation with lower solar elevations.

Contrary to expectations, diffuse beam SW↓ showed only slight and statistically insignificant differences between urban and rural sites. Changes in the nature of the diffuse beam summer and winter at similar solar elevations suggested more forward scatter of diffuse radiation in summer than winter. This led to the hypothesis of a different type of pollutant present over the city in the summer compared with the winter. While the summer pollutant promotes forward scatter of the diffuse beam, the pollutant present in winter tends to absorb and backscatter more radiation, with a lower proportion scattering forward.

Atmospheric transmissivity to direct beam radiation showed an increase in absolute terms towards summer due to a decreasing water vapour content in the atmosphere. However, urban/rural transmissivity differences showed an increase towards winter in response to increasing urban pollution. The average daily reduction in atmospheric transmissivity in the central city was 5.5%. The spatial pattern of atmospheric transmissivities across the city confirmed the urban/rural trend as measured at the fixed sites. Spatial patterns also showed the effect of topography, which altered certain atmospheric characteristics such as atmospheric vapour pressure.

Transmissivity variations between sites were found to be dominantly influenced by smoke pollution to the virtual exclusion of other variables over the autumn-winter period. However, related variables such as wind speed and direction, because of their effect on pollution dispersal and movement, were also found to be important. The continuation of radiation attenuation in summer in the absence of smoke pollution confirms the presence of a summer-type pollution not measured in this study.

LW$\downarrow$ was found to have a statistically significant urban excess amounting to an average 8.5% for clear days over the study period, an amount comparable with the only other similar study in the literature (Rouse and McCutcheon, 1972). The urban LW$\downarrow$ excess was found to have a seasonal trend being relatively greater in the winter period. Excess LW$\downarrow$ during the day was found to almost exactly balance the deficit of SW$\downarrow$ in urban areas, with the resultant daytime total energy income being almost identical for both sites. The urban excess was found to continue into the night, where it represented a real energy gain over rural areas. However, it was found that the absolute magnitude of excess energy was unlikely to be a significant cause of any heat island effects.

An examination of possible reasons for an urban/rural LW↓ difference again indicated the importance of atmospheric smoke, and in this respect the present study follows Rouse and McCutcheon (1972). This observation does not deny the importance of temperature as a determinant of LW↓, especially during the night when sensible heat flux from the warm city surfaces is absorbed and reradiated by the pollutant layer. The true effect of temperature appears to have been masked to an extent in this study by an urban thermal lag coinciding with peak LW↓ during the day.

A clearer understanding of the relative contribution pollution and urban warmth to the excess flux of LW↓ was not possible within the constraints of this study. It appears that the direct effect of SW↓ heating pollutants in the atmosphere during the day is dominant, while the influence of urban excess warmth becomes greater during the night. At this time it can directly influence the flux of LW↓ and can also indirectly influence LW↓ through heating of pollutants from heat flow from the surface. It is therefore partly the combined effect of pollution and urban temperature excess at night which is responsible for an increased LW↓. Data gathered from nightime mobile traverses, with LW↓ paralleling temperatures and pollution, substantiates this. Daytime traverses found that the LW↓ more closely followed pollution than other variables in trends across the city.

Applications of simple models designed to predict amounts of SW↓ and LW↓ achieved varied success. The surface climate simulator of Outcalt (1972) was quite successful in predicting direct beam radiation, which suggested that the particulate factor allowed for in this model has a real effect. However the simulator was less successful in predicting diffuse beam radiation and this was attributed to a forward/backscatter function in the simulator which did not account for the type of particulate found in this study. The Brunt equation was found reasonably accurate in prediction of LW↓ for the rural site, but was less successful in predicting LW$\downarrow$ at the urban site because it did not account for the higher urban atmospheric emissivity due to pollutants.

Divergences in radiation measured in this study have several important implications. The changes described for SW$\downarrow$ are important in determining the urban climate, as attenuation by its meaning implies heating within the atmosphere and a decreased radiation forcing function reaching the surface. This decreased forcing function can have an important effect on the urban heat balance (Oke, 1974). The decreased intensity of solar radiation reaching the surface also has implications for the use of this resource as an energy source. The changes described for LW$\downarrow$ have less startling implications, but the LW$\downarrow$ excess at night may help in maintenance of an urban heat excess although it has been proven that the flux of energy involved is too small to be a major cause of the urban heat island.

SUGGESTIONS FOR FURTHER RESEARCH

During this study, a number of problems and areas for possible further research were recognised. The data base which has been obtained will be invaluable for further consideration of urban effects on the radiation microclimate, as only part of it has been fully utilised in this thesis. Analysis has been restricted somewhat in this thesis by a need to have an adequate sample extending well into the winter of 1976. Consideration in this thesis was given largely to clear weather data, while an examination of variations in SW$\downarrow$ and LW$\downarrow$ under all weather conditions would have been useful. In addition, it would be an advantage in the examination of LW$\downarrow$, to consider effects both during daytime and nightime.

The spatial analysis in this study gave only general results and was relatively weak in the area of explanation of variables. Problems largely centred around the lack of accuracy in measurements, and the problem of not having on site pollution measurements. Both of these requirements were satisfied by the major sites and it seems that the establishment of a larger number of fixed stations would be of use in a further study such as this.

A better spatial pattern could also be obtained by remote sensing which is a procedure recently being used successfully to improve the climatic description of urban areas. While such methods as used by Outcalt (1972) and Lewis et al. (1976) are not amenable to the determination of atmospheric effects on the downward flux of radiation components in the lower part of the atmosphere, they could prove useful in determination of backscatter and LW$\uparrow$ influenced by the urban pollution layer.

Although the reasons for SW$\downarrow$ attenuation in urban areas are understood, the nature of scattering, reflection and absorption by aerosols is imperfectly understood. A consideration of these effects is of the utmost importance, both in urban areas and in terms of the global radiation budget. This study has outlined a degree of SW$\downarrow$ attenuation in the summer half year in the absence of smoke. The possibility of a photochemical type smog operating in the high-sun period in Christchurch could be investigated. Reasons for urban/rural variations in LW$\downarrow$ are still poorly understood, particularly with respect to the relative influence of pollution and temperature. Further investigation of LW$\downarrow$ in Christchurch should concentrate on a close monitoring of pollutants and especially of urban temperatures away from the surface. The use of simple predictive equations for incoming radiation in this study proved most valuable but there is room for even more sophisticated modelling to test mechanisms underlying urban climatology.

There is an important need in studies such as this for greater data collection in a vertical dimension. This applies to vapour pressure, smoke and temperature and would make possible the more accurate determination of reasons for LW$\downarrow$ variations. This would also obviate the need to use assumptions based on data from other areas. The use of atmospheric mixing depths in this study has indicated the usefulness of the measure as an indicator of atmospheric stability and pollution potential, and its application could easily be extended into the field of pollution forecasting.

At a more general level, the urban heat balance needs information on such variables as LW $\uparrow$, urban "soil" heat flow, evaporative and sensible heat flow. Lack of available instrumentation precluded the measurement of any of these in this thesis. Geiger (1972) states that: "a real understanding of micrometeorological processes can be only achieved when all factors involved in the heat balance are followed quantitatively through their sphere of influence." An examination of a larger number of heat balance components would allow the interactions between the different types of energy exchange to be sorted out more efficiently. However, despite these limitations, this study has suggested that urban effects on the radiation microclimate of Christchurch are significant and that further investigations along the lines suggested would bear useful results.

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APPENDIX I

Site Locations and View Factors

Major Sites

Airport	97.0
England Street	96.7

One Directional Traverse (giving nearest intersection)

(1)	Harewood/Russley Road	98.0
(2)	Memorial/Greers Road	97.9
(3)	Fendalton	90.5
(4)	Harper Avenue	75.0
(5)	Victoria/Kilmore Street	79.9
(6)	Armagh/Fitzgerald Avenue	84.6
(7)	England Street	83.1

Two Directional Traverse (giving nearest intersection)

North/South			East/West		
(A)	Stanleys/Harewood Road	98.0	(K)	Gilberthorpes/Waterloo Road	94.4
(B)	Greers/Harewood Road	94.3	(L)	Blenheim/Curletts Road	95.7
(C)	Papanui/Normans Road	90.6	(M)	Clarence/Warwick Street	94.1
(D)	Bealey/Springfield Road	84.9	(N)	Moorhouse/Antigua Street	92.2
(E)	Square	73.0	(O)	Railway Station	94.5
(F)	Ferry/Aldwins Road	92.8	(P)	Ferry/Aldwins Road	92.8
(G)	Colombo/Nutfield Avenue	95.6	(Q)	England Street	92.3
(H)	Dyers/McMillan Avenue	93.9	(R)	Pages/Farrington Avenue	96.6
(I)	Victoria Park	93.9	(S)	Brighton Foreshore	98.0
(J)	Sign of Kiwi	92.5			

APPENDIX II

Data Collection Programme

Fixed Sites

Because of mechanical failure, unfavourable weather and economics, the monitoring of $LW\downarrow$ and $SW\downarrow$ at the two major sites was not continuous over the study period (24 February - 4 July). Following is a list of days for which a complete set of data is available and from which the days used in this thesis were selected. A number of the gaps below have data available for one or other of the major stations.

February	March
24 - 25	1 - 4
27 - 29	13 - 22
	26 - 29

April	May
13 - 22	2 - 3
26 - 28	5 - 11
	15 - 19
	21 - 25
	28 - 31

June	July
1 - 7	1 - 2
10 - 19	4
25 - 30	

Mobile Traverses

One Directional

	Day	Night
March	18	
	19	19
		25
April	7[x]	
	17	
		21
	22	
May	3[x]	3[x]
		7
		13[x]
	21	21[x]
		23
		27[x]
	28[x]	
June		7
	11	
	12	
	14	14[x]
		26
		29

Two Directional

	Day	Night
August	9	
1975		10
	26	
June		11
1976		13
	25	
July	5	

[x] Disrupted by cloud.

APPENDIX III

Errors in Measurement.

Apart from the assumption already made in the text, the assumption that all errors are random in nature has to be made when errors are combined using standard techniques.

Errors between paired instruments were computed from the calibration data using the formula

$$Sy - x = (\sqrt{1 - r^2}) \times Sy$$

where S = Standard deviation.

After derivation of errors from the above standard error of estimate the SW$\downarrow$ and LW$\downarrow$ instrumental errors were combined with possible sampling errors and total errors calculated over various time periods in the method of Brooks and Carruthers (in Stanhill, 1965). They suggested that the standard deviation of climatological measurements is inversely proportional to the square root of the length of period concerned. This resulted in data included in Table 2.4

This method of computation of errors includes such problems as non-linearity of instrumental response but does not include for the progressive errors that can occur such as moisture or weathering effects on the domes of the radiation sensors.

APPENDIX I V

Computer Programme Listing

Four small programmes were developed in the course of this study to be used in conjunction with the Departmental Computer. The language is "Basic" and it is hoped that the listing of these may be of use to any further worker in this field. Apart from these listed below, further standard programmes were used for t-tests, simple linear regression and multiple regression.

Programme information is listed below followed by the programme listings.

1) "SHADCORN" - corrections for errors induced by shadow ring.
   Inputs are: width and radius of shadow ring, latitude and solar declination.

2) "TRANS" - calculation of atmospheric transmissivity coefficients.
   Inputs are: station name, solar time, date, latitude, solar declination, radius vector, air pressure and measured direct beam radiation.

3) "SUNGEN" - simulation of SW radiation characteristics.
   Inputs are: station name, date, latitude, solar declination, dust particles/cc, precipitable water (mm), pressure, albedo and radius vector.

4) "HUMID" - calculates vapour pressure from temperature and humidity characteristics.
   Inputs are: station name, date, time, dry bulb temperature, wet bulb temperature, relative humidity and air pressure.

1.) 'SHADCORN'

```
10 REM "SHADCORN" AFTER DRUMMOND (1955) ARCH MET BIOK GEOPHYS
20 DEFFNR(X)=X/57.29557
30 PRINT "ENTER VALUES AS REQUESTED":PRINT "WIDTH OF SHADOW RING
(MM)";:INPUT B:PRINT "RADIUS OF RING(MM)";:INPUT R
35 PRINT "LATITUDE";:INPUT L:L8=FNR(L)
40 SELECT PRINT 215:PRINT "SHADOW RING CORRECTIONS FOR WIDTH=";B
;"MM RADIUS=";R;"MM LATITUDE=";L;"(DEG)":PRINT " ":PRINT "SUNS D
ECLINATION   ISOTROPIC    CLOUDLESS   OVERCAST":SELECT PRINT 005

50 PRINT "SUNS DECLINATION";:INPUT D:D8=FNR(D):SELECT R
60 T0=#PI+ARCCOS(-TAN(D8)*TAN(L8))
70 C=2*B*((COS(D8))^3)*(SIN(L8)*SIN(D8)*T0+COS(L8)*COS(D8)*SIN(T
0))/(#PI*R)
80 C1=1/(1-C):C2=C1+C1*0.07:C3=C1+C1*0.03
90 SELECT PRINT 215:PRINTUSING  95,D,C1,C2,C3
95%     ###.##          ##.###          ##.###       ##.###
100 SELECT PRINT 005: PRINT "DO YOU HAVE SOME MORE Y OR N";:INPU
T A$: IF A$="Y" THEN 50
110 END
```

2.) 'TRANSM'

```
10 REM "TRANSM" CALCULATION OF TRANSMISSIVITY COEFFICIENTS
20 REM INPUT DATA REQUIRED = STATION, DATE, TIME, LATITUDE
30 REM SOLAR DECLINATION, RADIUS VECTOR, PRESSURE, MEASURED DIRE
CT RADIATION
35 SELECT PRINT 005
40 PRINT  "ENTER STATION NAME";:INPUT A$:PRINT "LATITUDE";:INPUT
L1
45 SELECT PRINT 215(80):PRINT "STATION", A$:PRINT "LATITUDE",L1:
SELECT PRINT 005
50 PRINT  "DATE";:INPUT B$: PRINT "DECLINATION";:INPUT D1:PRINT
"RADIUS VECTOR";: INPUT R
60 SELECT PRINT  215 :PRINT  "DATE   ", B$:PRINT "DECLINATION",D
1: PRINT  "RADIUS VECTOR", R
65 PRINT "TIME   HOUR    ZENITH    PRESSURE   OPTICAL   DIRECT
RADIATION  TRANSMISSIVITY"
70 PRINT "         ANGLE    ANGLE      (MB)        DEPTH     MEAS
   EXP       COEFFICIENT"
75 PRINT "         (DEG)     (DEG)                              (MW/CM
^2)": SELECT PRINT 005
80 PRINT  "TIME HRS";:INPUT T1:PRINT "MINS";:INPUT T2:PRINT  "PR
ESSURE";:INPUT P: PRINT "MEASURED DIRECT RADIATION";:INPUT S:SEL
ECT PRINT 215
85 SELECT R : L2=L1/57.29578:D2=D1/57.29578
90 T3=T1+T2*(1/60):H=(12-T3)*15:H1=H/57.29578
100 C2=SIN(D2)*SIN(L2)+COS(D2)*COS(L2)*COS(H1)
110 Z=ARCCOS(C2):H2=(#PI/2)-Z:Z1=Z*57.29578
120 M=(2/SQR(ABS((SIN(H2))^2+0.003147+SIN(H2))))*(P/1013)
130 S1=(1360/(R^2))*SIN(H2):T4=(S/S1)^(1/M)
140 PRINTUSING 145,T1,T2,H,Z1,P,M,S,S1,T4
145 % ## ## ##.##   ###.#     ####.#     ##.##      ###.##    ####.#
#        #.####
150 SELECT PRINT 005 :PRINT "MORE DATA FOR SAME DAY Y OR N";:INP
UT C$: IF C$ = "Y" THEN 80 :PRINT "NEW DAY SAME STATION Y OR N";
:INPUT D$: IF D$="Y" THEN 50
160 PRINT  "NEW STATION Y OR N";:INPUT F$: IF F$="Y" THEN 40
170 END
```

3.)'SUNGEN'

```
10 REM SUBROUTINE "SUNGEN" FROM OUTCAULTS CLIMATE SIMULATOR
20 REM READ DATA
30 PRINT "TYPE STATION NAME AND DATE SEPARATED BY COMMAS":INPUT
A$,B$
40 PRINT "TYPE IN INPUT DATA ":PRINT "LATITUDE";:INPUT L1:PRINT
"SUNS DECLINATION";:INPUT D1:PRINT "PRESSURE";:INPUT P:PRINT "DU
ST PARTICLES/CC";:INPUT D:PRINT "PRECIP. WATER(MM)";:INPUT W:PRI
NT "ORB. RAD. VECTOR";:INPUT R:PRINT "ALBEDO";:INPUT A:DEFFNA(X)
=X/57.29578
45 SELECT PRINT 215 :PRINT "SW RADIATION FOR  ";A$, "  ON  ";B$,
 "LATITUDE  ";L1,,,"SUNS DECLINATION  ",D1,,,"PRESSURE  ",P,,,"D
UST PARTICLES/CC  ",D,,,"PRECIP.WATER(MM)   ";W
46 PRINT  "ORB.RAD.VECTOR   ";R,,,"ALBEDO   ";A
47 PRINT  "  TIME     EX.    TERR.     DIRECT     DIFFUSE     BACKSCT
   TOTAL."
50 FOR I=1 TO 96 STEP 4:S3=(I-1)/4:H1=FNA((S3*15)-180):R2=FNA(L1
):R3=FNA(D1):C2=SIN(R2)*SIN(R3)+COS(R2)*COS(R3)*COS(H1)
60  X1=ABS(1/C2)*(P/1013):A1=-0.089*(((P*X1)/1013)^0.75)-0.174*(
((W*X1)/20)^0.6):S5=-0.083*((D*X1)^0.9):IF C2>0 THEN 70:C2=0
70  E1=(2000/R^2)*C2:B1=E1*EXP(A1+S5):D2=0.5*E1*(1-EXP(S5)):S4=B
1+D2:B2=0.5*A*S4*(1-EXP(S5)):S1=S4+B2:S2=S1-B2
80 IF E1=0 THEN 90:PRINTUSING 85,S3,E1,B1,D2,B2,S1
85%####.##     #####.#     ######.#      #####. #####.#     ####
.#     ######.#
90 NEXT I
100 END
```

4.)'HUMID'

```
10 REM "HUMID". CALCULATION OF HUMIDITY FROM DRY BULB WET BULB
TEMPERATURE OR REATIVE HUMIDITY.
20 REM FORMULAE FOR SATURATION VAPOUR AS A FUNCTION OF
TEMPERATURE FROM SMITHSONIAN TABLES V.114,P.350.
30 PRINT "ENTER STATION NAME";:INPUT A$:PRINT "DATE";:INPUT B$:P
RINT "INDICATE WHETHER REL HUMIDITY(RH) OR WET BULB TEMP(TW) WIL
L BE INPUT";:INPUT C$
40 E1=2.3026 : DEFFNW(T)=10^(-7.90298*((373.16/T)-1)+5.02808*LOG
(373.16/T)/E1-1.3816E-7*(10^(11.344*(1-T/373.16))-1+8.1328E-3*(1
0^(-3.49149*((373.16/T)-1))-1)+LOG(1013.246)/E1)*10
50 DEFFNI(T)=10^(-9.09718*((273.16/T)-1)-3.56654*LOG(273.16/T)/E
1+.876793*(1-(T/273.16))+LOG(6.1071)/E1)*10
60 SELECT PRINT 215:PRINT "CALCULATIONS OF HUMIDITY CHARACTERIST
ICS FOR  ";A$;"ON";B$
70 PRINT " ":PRINT "TIME  TD   TW  PRESSURE  REL. HUMIDITY  VAPO
UR PRESSURE  SPECIFIC HUMIDITY":PRINT "(HRS)   (C)   (C)    (MB)
   (%)    (MB)      (G/KG)"
80SELECT PRINT 005:PRINT "ENTER VALUES FOR COMPUTATIONS":PRINT "
TIME";:INPUT T1:PRINT "DRY BULB TEMP(C)";:INPUT D1:PRINT "WET BU
LB TEMP(C) OR REL HUMID(%)";:INPUT Z1:PRINT "PRESSURE(MB)";:INPU
T P
90 D2=D1+273.16:IF D2<273.16 THEN 100:S1=FNW(D2):GOTO 110
100 S1=FNI(D2)
110 IF C$="RH"THEN 140:W1=Z1:W2=W1+273.16:IF W2<273.16THEN 120:S
2=FNW(W2):GOTO 130
120 S2=FNI(W2)
130 R=S2/S1:R1=R*100:GOTO 200
140 R1=Z1:R=R1/100:S2=R*S1:W3=D2:W4=W3-40:W2=(W3+W4)/2
150 IF W2<273.16 THEN 160:S3=FNW(W2):GOTO 170
160 S3=FNI(W2)
170 IF ABS(S2-S3)<0.01 THEN 190:IF S3<S2 THEN 180:W3=W2:W2=(W2+W
4)/2:GOTO 150
180 W4=W2:W2=(W2+W3)/2:GOTO 150
190 W1=W2-273.16
200 E=R*S1:Q=(.622*E/(P-E))*1000:SELECT PRINT 215
210 PRINTUSING 220,T1,D1,W1,P,R1,E,Q
220% #### ###.#  ###.#     ####.#      ###.##      ###.##      ###
.##
230 SELECT PRINT 005:PRINT "MORE VALUES Y OR N";:INPUT D$:IF D$=
"Y" THEN 80
240 END
```